Chapter 2: Magnets and the Lattice

Epoxy on both your houses!

- ROMEO AND JULIET

This chapter deals with the magnets that are used to maintain circulating beam in the Main Injector. For all of the effort that goes into building and maintaining the magnets in an accelerator, they have a rather limited role: to constrain the motion of the particles so that they are prevented from leaving the machine. This chapter has an even more limited role, dealing primarily with beam already circulating in the accelerator. Transfers into and out of the Main Injector will be discussed in the chapter on Beam Transfer Lines.

Forces

The basic mathematical equation describing how a charged particle interacts with electric and magnetic fields is:

$$\vec{\mathbf{F}} = \mathbf{q}\vec{\mathbf{E}} + \mathbf{q}\vec{\mathbf{v}} \times \vec{\mathbf{B}}$$

where $\vec{\mathbf{F}}$ is the force on the particle, q is the charge of the particle, $\vec{\mathbf{E}}$ is the electric field, $\vec{\mathbf{v}}$ is the velocity of the particle, and $\vec{\mathbf{B}}$ is the magnetic field.

The quantities with the arrows—that is, everything except for the charge—are vectors. With a vector, the direction of the field or force must be taken into account, in addition to the strength or magnitude. The × symbol represents a form of vector multiplication known as a cross product.

The first term of the equation, $q\vec{\mathbf{E}}$ represents the force created by the electric field. The electric field is crucial to the operation of any accelerator, because it is the only means available for changing the energy of the beam. The direction of the accelerating force is the same as the direction of the electric field. The energy-changing electric field belongs to the realm of the

RF systems; it will be dealt with in excruciating detail in a later chapter. For now, strike $\mathbf{q\vec{E}}$ from the equation.

The remaining term, $\mathbf{q\vec{v}\times\vec{B}}$, describes the influence of the magnetic field. The charge, q, is constant. Although actually measured in coulombs, for our purposes it can be reduced to (+1) for protons and (-1) for antiprotons.

The speed of the particle, surprisingly enough, changes only slightly as a particle is accelerated from 8 GeV to 150 GeV. This odd behavior is due to relativistic effects and will be explained later, but for now it can be assumed that the magnitude of $\mathbf{\vec{v}}$ is constant. Normally measured in, say, meters per second, for our purposes the velocity can be reduced to a +1 for protons and -1 for antiprotons. The difference in "polarity" is because the velocity vector requires a direction, and the frame of reference used here is that of the proton direction in the Main Injector.

The magnetic field $\mathbf{\vec{B}}$ also has a direction. Often the strength and direction of the field are visualized as "field lines" connecting one pole of a magnet to another pole. The magnitude of $\mathbf{\vec{B}}$ can be expressed in units of gauss, or in Tesla. One Tesla is equivalent to 10^4 gauss.

The cross-product, $\mathbf{q\vec{v}\times\vec{B}}$, means that only the components of $\mathbf{\vec{v}}$ and $\mathbf{\vec{B}}$ which are perpendicular to each other will generate a force. That is, if $\mathbf{\vec{B}}$ is in exactly the same direction as $\mathbf{\vec{v}}$, there is no magnetic force on the particle. Conversely, the maximum force is produced when the magnetic field is exactly perpendicular to the direction of motion. Moreover, the force $\mathbf{\vec{F}}$ is itself perpendicular to both the direction of motion and the direction of the field.

There is an interesting consequence of $\mathbf{\vec{F}=q\vec{v}\times\vec{B}}$ that, as it has turned out, has been the single most important driving force behind the construction of the large accelerators built over the last two decades. If a proton (positive charge) passes through a magnet, it will see force of:

$$\mathbf{\vec{F}} = (+1)(+1)\times\mathbf{\vec{B}}$$

If an antiproton (negative charge) passes through the same magnet in the opposite direction, it will see a force of:

$$\vec{\mathbf{F}} = (-1)(-1)\times\vec{\mathbf{B}},$$

its velocity being negative because it is going "backwards" relative to the protons. The result is that $\mathbf{q}\vec{\mathbf{v}}$, and therefore $\vec{\mathbf{F}}$, is identical for both particles. As long as the particles are traveling in opposite directions, the same magnets can be used for both kinds of particles. This fact has spawned an entire industry of antiparticle sources, including Fermilab's Antiproton Source, and will be an indispensable part of the role that the Main Injector and the Recycler will play during Collider Mode. Remember from "Modes of Operation" that the protons travel in a counterclockwise direction, and the antiprotons travel clockwise.

Types of motion

The two fundamental types of particle motion are longitudinal and transverse. Longitudinal motion of a particle is in a "forward" or "backward" direction with respect to the desired path of the beam. Transverse motion is perpendicular with respect to the longitudinal, and can be horizontal, vertical, or some combination of the two. When particle motion is superimposed on coordinate axes, the x-axis represents the horizontal, the y-axis the vertical, and the z-axis the longitudinal.

In accelerators, then, the forward motion of the particles is longitudinal. The magnetic field is always set up so that it is perpendicular to the primary direction of motion, the field lines are usually set up to be either horizontal or vertical. The magnetic force itself is perpendicular to the direction of motion and to the field lines. If the field lines are vertical, the force will bend the beam horizontally, and if they are horizontal, the beam will be bent vertically.

That means that no magnet, no matter how it is designed, can change the longitudinal motion of a particle; magnets are only capable of influencing transverse motion. Magnets are excellent devices for bending and focusing the beam, but useless for changing its energy.

A magnetic field is created whenever an electric current flows in a conductor. The stronger the current, the stronger the magnetic field. It is necessary to use electromagnets whenever the beam changes energy, although the magnets themselves do not change the energy, their bending strength must still track the energy in order to constrain the beam. Usually (but not always), the conductor is arranged as a coil; the number of turns in the coil, along with the amount of current, is proportional to the strength of the field.

There are also permanent magnets, like those pinning down shopping lists on a refrigerator door, which do not explicitly depend on flowing current. The magnetic field comes from the unbalanced “spin” of the electrons in certain materials. Most of the magnets in the 8 GeV line and the Recycler are permanent magnets; the beam energy in both cases is held constant at 8 GeV. The magnetic material used is strontium ferrite.

The disadvantage of electromagnets is that they require a great deal of infrastructure, including large amounts of electrical power and elaborate water systems for keeping them cool. Permanent magnets do not require the same infrastructure, but there is the disadvantage that once the field is fixed it is difficult to change.

Main Dipoles

Dipoles are magnets in which the entire beam passing through them is pushed in the same direction. The two poles are the familiar “north” and “south” poles, although those terms are rarely used at Fermilab.

Dipoles in the Main Injector come in several sizes.

- The main dipoles described in this section weigh several tons apiece.
- There are also corrector dipoles that weigh a few hundred pounds apiece (but these magnets won’t be described until later in this chapter).

- There are permanent magnet dipoles used in the MI-8 line and the Recycler.
- Finally, there are specialized dipoles in the beam transfer lines, which will be covered in another chapter.

Fig. 2-1 shows the ring-wide distribution of the main dipoles; each small box represents one of the main dipoles. These dipoles are responsible for bending the beam around the curvature of the ring. The “A” and “B” dipoles, shown in dark blue, are 6 meters long. The “C” and “D” dipoles, in light blue, are 4 meters long.

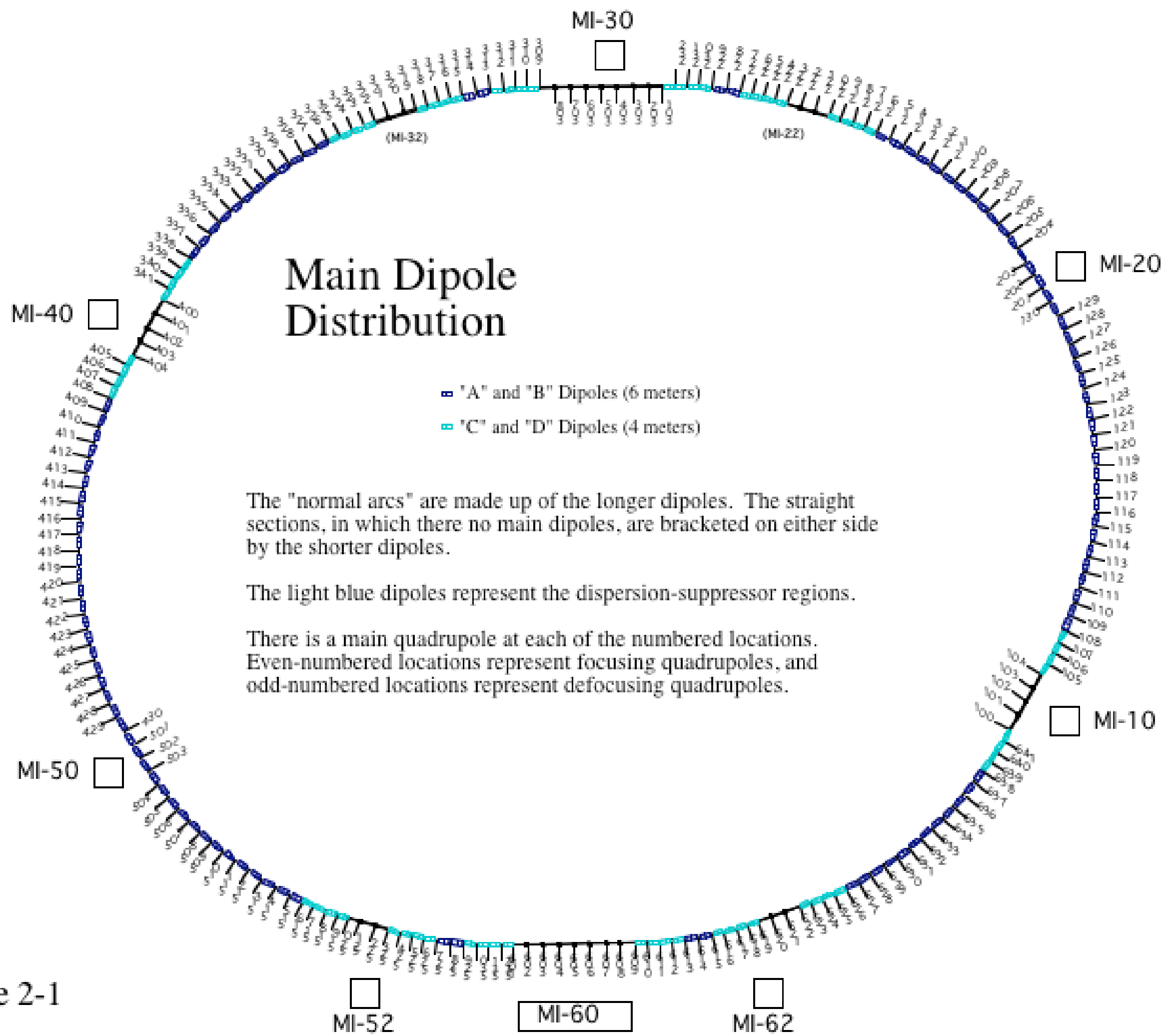


Figure 2-1

The scheme for numbering locations in the Main Injector is based on the direction that the protons travel. Notice in the diagram that the numbers increase in the counterclockwise direction, beginning at MI-10; MI-10 was chosen as the starting point because that is where protons first enter the machine from the MI-8 line. The first series of numbers, from MI-10 to MI-20, begins with "100." A series of numbers in the 200's begins at MI-20, with a new series being launched at each of the major service buildings.

Notice in Fig. 2-1 that wherever the main dipoles are present, there is one pair between each numbered location. "A" and "B" magnets are always paired together, as are the "C" and "D" magnets. Within each pair, they are arranged alphabetically, also in a counterclockwise direction. (The convention in this book is that side-view diagrams will be drawn from the perspective of an observer standing in the tunnels. Since the magnets line the outside wall of the tunnel, this convention will soon lead to some awkward pictures: numbers and letters will increase from right to left. It will be uncomfortable for those trained in the English language or number lines, but get used to it. Think like an Egyptian.) There will be a more detailed description of the numbering system after the many different kinds of magnets have been introduced.

The regions made up of "A" and "B" dipoles are called the "normal" arcs. Where there are no main dipoles, there is no curvature; these regions are the straight sections. Altogether, there are 8 straight sections in the Main Injector. They are used for a variety of specialized functions, usually involving beam transfer. The "C" and "D" magnets are found in the dispersion suppressor regions, which act as bridges between the normal arcs and the straight sections. A more complete explanation of these different parts of the ring will appear later in the chapter.

All four types of magnets, although they differ in other respects, are identical in cross-section; a typical slice of a main dipole magnet is shown in Fig. 2-2. The beam travels inside the elliptical beam pipe (sometimes referred to as the beam tube) that runs along the central axis of the magnet. Obviously, it is inside the beam pipe where the strength and direction of the magnetic field are the most important.

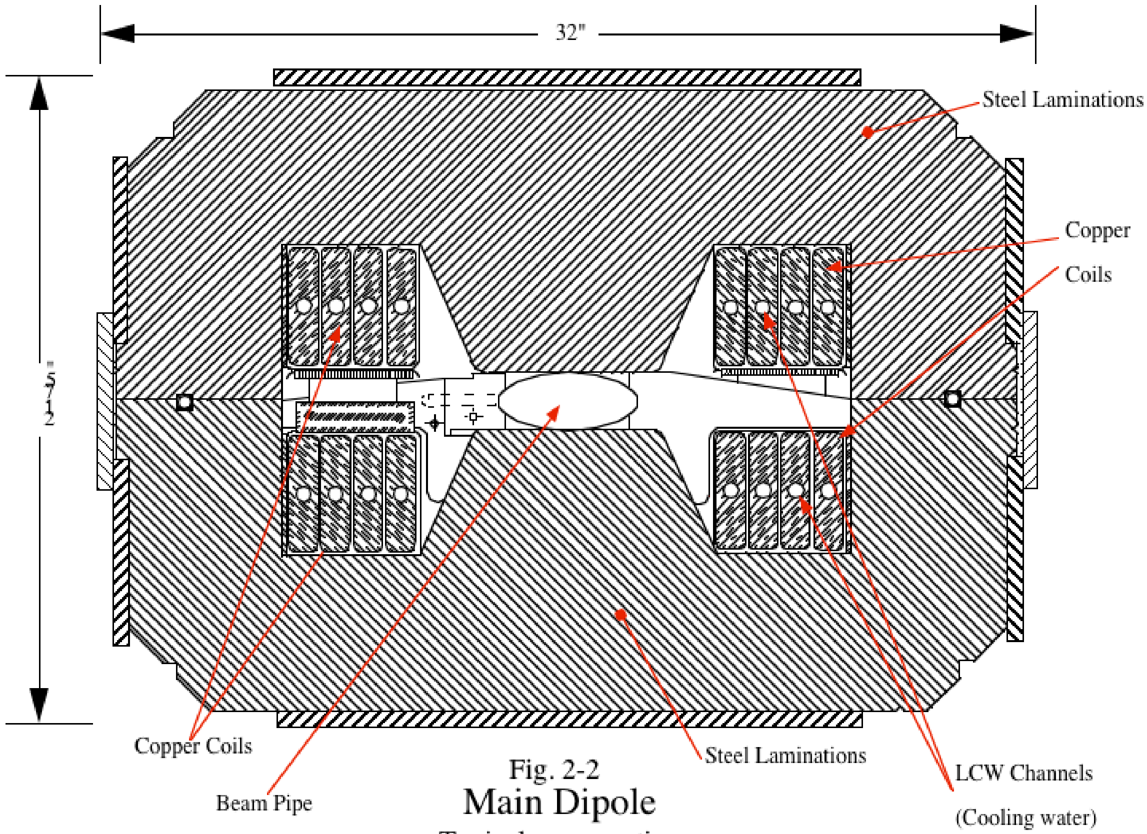


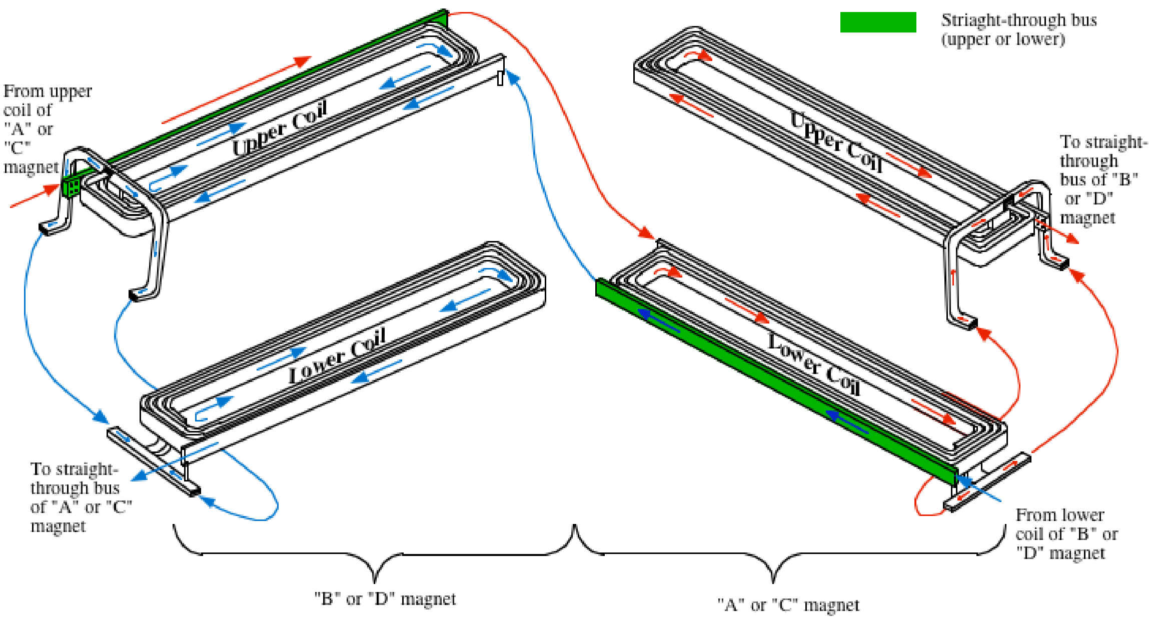
Fig. 2-2
Main Dipole
Typical cross section

Current flowing in a conductor creates the magnetic field, and, as with most electromagnets, the conductor is wound into a coil. A coil produces the effect of having several adjacent conductors working together to create the magnetic field. Fig. 2-3 shows what the coils of a pair of main dipole magnets would look like if all of the surrounding material were removed; the view of the upper and lower coils has been exploded in order to clarify the upcoming description of current flow.

The magnetic field near a current-carrying conductor can be visualized by grasping the conductor with your right hand (in your imagination, of course—to actually do so is probably a violation of LOTO). If your thumb is pointing in the direction of the current, your fingers will naturally “curl around” the conductor in the same direction as the magnetic field. In the figure below the current flow in a main dipole is schematically represented. The perspective for a main dipole would be looking downstream in the proton direction.

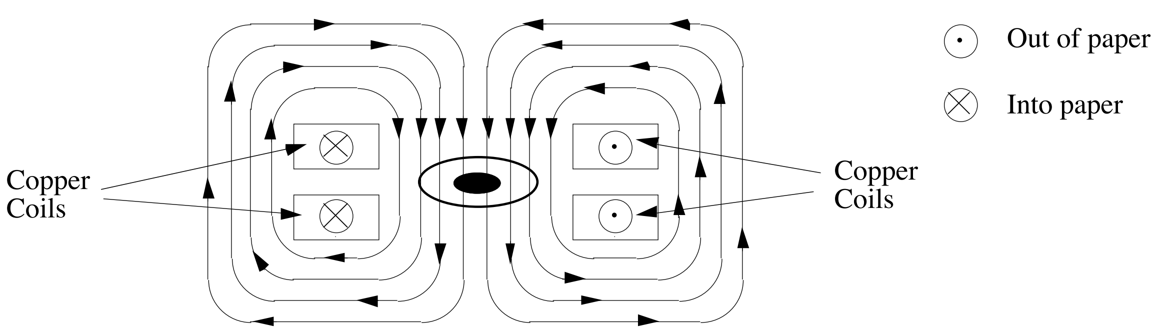
Fig. 2-3

Main Dipole Coil Current

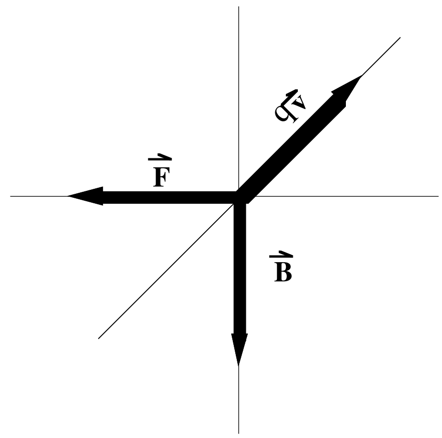


Current flow in a pair of main dipole magnets. Only the coils are shown; the view has been exploded for clarity.

Although the magnetic field "wraps around" the copper coils, it is uniformly pointing downward over the region of the beampipe. Disregarding the effects of the surrounding material, the strength of the field is proportional to the current in the coil. (Here, and throughout this book, conventional current—in which current flows from positive to negative—is represented instead of electron flow, because that is what countless generations of engineers have been brainwashed into using.)

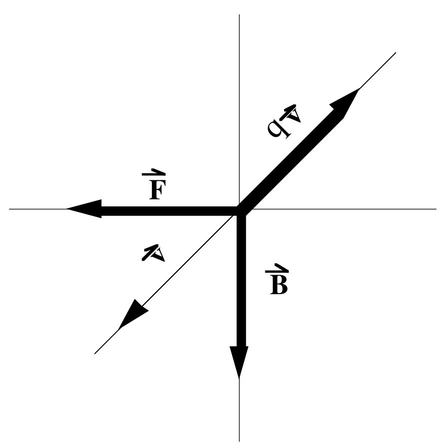


The direction of the force is determined from the right-hand rule, which itself is derived from $\mathbf{q}\vec{\mathbf{v}} \times \vec{\mathbf{B}}$. (A quick-thinking graduate student caught making a gesture to his professor, originally developed the right-hand rule.) Hands are difficult to draw in software, but the directions of the vectors can be shown on three coordinate axes. The force on a proton, with its positive charge, is shown in the figure below:



Here, $\vec{\mathbf{v}}$ is pointing "forward" in the proton direction. $\vec{\mathbf{B}}$ is pointing down, as in the picture on the previous page. $\vec{\mathbf{F}}$ is pointing to the left, so that the protons experience a force pointed towards the inside of the ring. This is how it should be, since it is this force that balances that irritating Newtonian tendency for the protons to move in a straight line and leave the beam pipe.

The force on antiprotons traveling backwards is the same; even though $\vec{\mathbf{v}}$ is in the opposite direction, the force is in the same direction because q is negative:

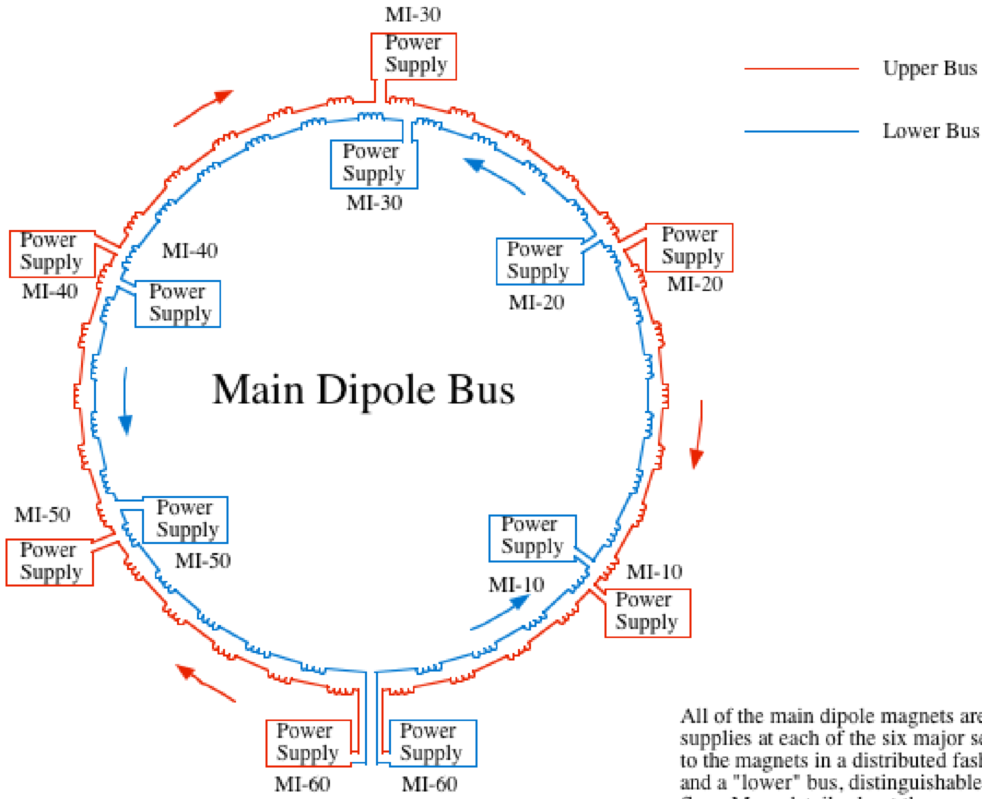


Returning to Fig. 2-2, recall that the ellipse in the center represents the beam pipe. The current-carrying coil is represented by the four sets of tall rectangles, 1" wide and 4" tall. The coil, made of copper, needs to be capable of carrying a peak current of 9400 amps. The current flows in one direction on the right side of the magnet and the other direction when it returns on the left. As the magnetic field "wraps around" the two sets of conductors, the field lines all point in the same direction in the region of the beam pipe.

The number of turns in a coil, and the amount of current in a coil, determines what the field strength will be. An "upper" bus and a "lower" bus ("upper" and "lower" referring to the relative locations of the conductors as they enter the magnets) power the coils. (The term bus refers to the entire length of the conductor, including the coils, the power supplies, and all of the connections between them.)

The upper and lower busses are not actually distinct entities, but "turn around" inside the power supplies at MI-60, as shown in Fig. 2-4. Since current in the upper bus is flowing in the opposite direction from that in the lower bus, the inductive load created by the magnets is balanced. (For those having trouble with that concept, an emergency section on inductance is located at the end of the chapter.) In addition, since current flowing in a loop also creates an external magnetic field that is perpendicular to the loop, having two loops of opposite polarity means that the two fields will cancel each other.

The electrical connections to the Main Injector magnets are a bit more complicated than with some other magnets. To trace the flow of current through an "A" and "B" pair—a "C" and "D" pair would be identical, except for the length—review Fig. 2-3. "A" and "B" magnets are ordered in the proton direction (counterclockwise). As mentioned earlier, when standing in the tunnel and looking at the magnets they are "read" from right to left. "A" will be on the right, "B" on the left.



All of the main dipole magnets are in series. Two power supplies at each of the six major service buildings supply power to the magnets in a distributed fashion. There is an "upper" bus and a "lower" bus, distinguishable by the direction of current flow. More details about the power supplies can be found in Chapter 3.

Fig 2-4

The top and bottom coils of each magnet each have four turns, but the main dipole magnets are designed so that there are “straight-through” conductors that only constitute half of one turn. Each bus powers a straight-through section in one magnet and both the top and bottom coils in the other.

Starting with the upper bus, current enters the “B” magnet at the downstream side, on the left. It first powers the straight-through bus at the top coil. Notice that this copper bar is not electrically connected to the rest of the coil, but because of the direction of its current, it contributes to the magnetic field as if it were. The bar emerges at the upstream side of the “B” magnet, where it is connected to the lower coil of the “A” magnet. The lower coil makes 3 1/2 turns, each turn nesting inside the previous one. At the upstream end of the “A” magnet, a braided copper jumper carries the current to the upper coil. The jumper temporarily divides the current into two branches so that there is no net magnetic field at the end of the magnet. Current enters the top coil on the inside turn and completes four full turns, working its way to the outside. Notice that the upper bus enters the "B" magnet at the top and leaves the "A" magnet at the top, making it easily identifiable in the tunnel.

Current from the lower bus enters the straight-through bus of the lower coil of the "A" magnet, adding the final half turn needed to complete the coil. From there it goes to the upper coil of the "B" magnet, powering 3 1/2 turns as it works its way to the inside. The external jumper carries the current to the inside turn of the lower coil. The current works its way to the outside of the coil, and when the four turns are complete, it moves on to the next pair.

To summarize: The upper bus powers 7 1/2 turns of the "A" magnet and half a turn of the "B" magnet. The lower bus powers 7 1/2 turns of the "B" magnet and half a turn of the "A" magnet. This arrangement means that the voltage across the pair of magnets is minimized, since the inductive load is shared between the two busses. Moreover, placing the return bus inside the magnets reduces the amount of copper that has to be purchased, as well as reducing the total amount of electrical resistance that the power supplies must overcome.

Look again at Fig. 2-2, and compare it to Fig 2-3. The cross-section is representative of any main dipole; for the following discussion it can be assumed that it is an "A" dipole, looking downstream in the proton direction (counterclockwise in the tunnel). Protons in the elliptical beam pipe are moving into the paper. For the most part, current in the coils is coming out of the paper on the right-hand side, turning around at the reader's nose, and going into the paper on the left-hand side. The two half-turns that do not turn around are the straight-through bar at the lower left, powered by the lower bus, and the final half-turn at the upper right, which connects to the upstream pair of magnets.

Although the current is continuous in a given bus, the individual turns within the magnet must be electrically insulated from each other. A turn-to-turn short would diminish the magnetic field for at least some of the length of the magnet. Voltages between turns on a given bus can be large, creating the possibility of arcing across the gap, destroying the insulation, and creating a short. The risk is even higher with the straight-through bus and adjacent coils, because the voltage between them can be as high as 2,000 volts. Several layers of fiberglass, impregnated with epoxy, are used to insulate the turns. Extra insulation surrounds the straight-through bus.

The holes in the coil are for the low conductivity water (LCW) used to cool the magnets. The water systems will be discussed in a later chapter.

Laminations

The hatched region in Fig. 2-2 represents the steel laminations surrounding the coils. The steel is of a specific high permeability type that concentrates the magnetic field. The laminations are 1.5 mm thick and are stamped out by the thousands in dies. When building a magnet, they are stacked and placed in a press. The reason a solid piece of steel is not used is that large eddy currents would develop in the presence of the magnetic field. The eddy currents would not only dissipate energy, but would change the character of the field. Small eddy currents still occur within the thin laminations, but they are not nearly as disruptive.

Of course, the laminations must be electrically isolated from each other or there is no point in using them. The ends of the magnets are constructed separately from the center section. Laminations for the end packs of the dipoles are coated in epoxy and heated until the epoxy cures. The epoxy provides cohesion for holding the laminations together as well as electrical insulation between the laminations. Laminations in the center section of the magnet are pre-coated with a plastic shield, which serves as electrical insulation; cohesion is maintained by welding a plate to the laminations while they are still in the press. Should the magnet need repair, it will be easier to remove the welded plate and separate the laminations than to deal with laminations that are glued together.

The reason for building the end packs separately is that in any magnet of finite length, the magnetic field is relatively uniform in the center but becomes geometrically complex toward the ends. The steel laminations, which are the most important factor in determining the shape of the field, must be assembled most carefully in the end packs.

The steel should not be thought of as a continuous entity, even within the laminations, because it is actually made up of innumerable microscopic crystals. Each individual crystal—also known as a magnetic domain—is a permanent magnet with its own magnetic field, but in a magnet that has not been powered the crystals are randomly oriented so that there is no net field. When current begins to flow in the coil, the field created by the coil begins to align the domains and the steel itself begins to contribute to the field.

Although the steel contributes much in the way of field strength and shape, it also introduces some problems. One is hysteresis, or the tendency for magnetic domains to remain as they are. Fig. 2-5 shows the hysteresis curve for a main dipole magnet. The horizontal axis is the "magnetizing force," initially supplied by the coil current, and the vertical axis is the component of the field created by the steel. (The magnetizing force is measured in units known as oersteds. Don't worry excessively about how oersteds are defined, but be aware that the magnetizing field initially comes from the coil current. As the magnetic domains are aligned with the field, they also begin to contribute to the magnetizing force.) The magnetizing force can be either positive or negative, depending on the polarity of the field. Point "A," at the center of the diagram, represents a magnet that has never been energized. There is no current in the coil, no magnetizing force, and no field. As current of the proper polarity energizes the coil, a field develops along with the magnetizing force, and the path from "A" to "B" is traced. This path would be taken when ramping to flattop. Notice that the curve begins to flatten as the magnetizing force reaches large values. This is because nearly all of the magnetic domains have been aligned: a phenomenon known as saturation. In the Main Injector, the effects of saturation begin to appear around 120 GeV. Also notice that the path is not linear, and that the magnetic field in the dipoles is not always directly proportional to the current.

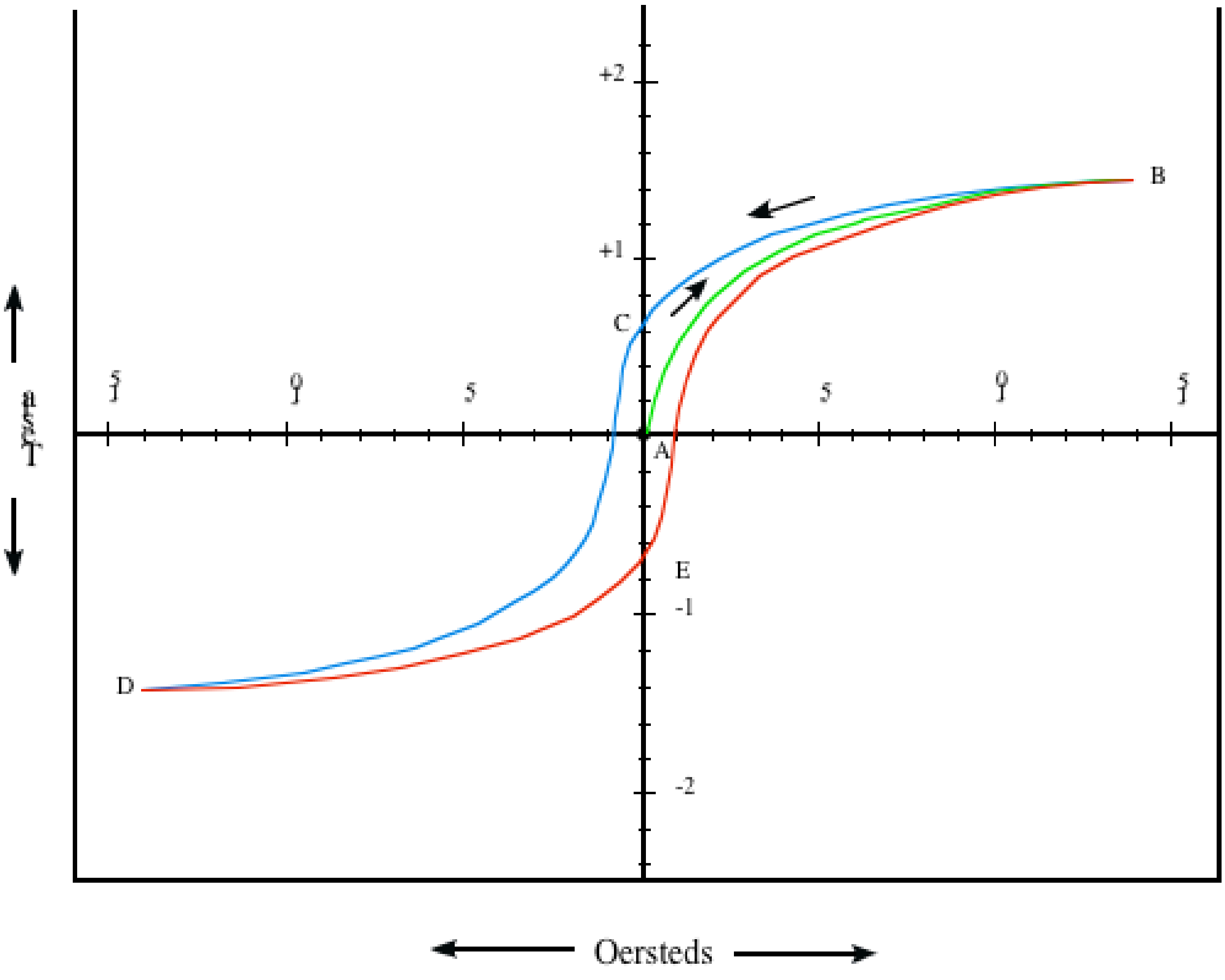


Fig. 2-5
Hysteresis in a Main Dipole Magnet

When the current in the coil is reduced, as when the ramp returns toward the 8 GeV level, the magnetic domains are already aligned; this "fossil" field remains considerably stronger than what would be expected based on the coil current alone. In fact, at point "C," there is still a significant field left over even when the magnetizing force is zero. Hysteresis is this lack of ability to retrace the magnetization curve due to the history of the magnetic domains.

Hysteresis, saturation, and nonlinearity all have potentially adverse effects on the performance of the Main Injector dipoles. Strategies for dealing with these phenomena are implemented through the software that controls the power supplies.

The steel is grounded and obviously has to be insulated from the coils. A breach of the insulation between the coil and the steel would create a coil-to-ground short. Coil-to-coil and coil-to-ground shorts were all too frequent in the Main Ring, creating many hours of downtime for every failure. It is hoped that the Main Injector will be more robust.

Main Quadrupoles

The dipoles perform the necessary function of bending the beam around the curvature of the ring, but that is not sufficient to keep the beam inside the beam pipe. The beam consists of billions and billions of particles; in addition to their longitudinal motions, each one has its own unique transverse motion. Without some kind of focusing, the particles would spread out and within a few dozen feet would be lost from the machine.

Focusing the beam is done with quadrupole magnets. Quadrupoles, as you might guess, have four poles. The main quadrupoles, which are similar in cross-sectional size to the main dipoles but somewhat shorter, will be described in this section. There are also smaller quadrupoles, which will be described later.

The main quadrupoles in the Main Injector come in three lengths: 84”, 100”, and 116," but are virtually identical in cross-section (Fig. 2-6).

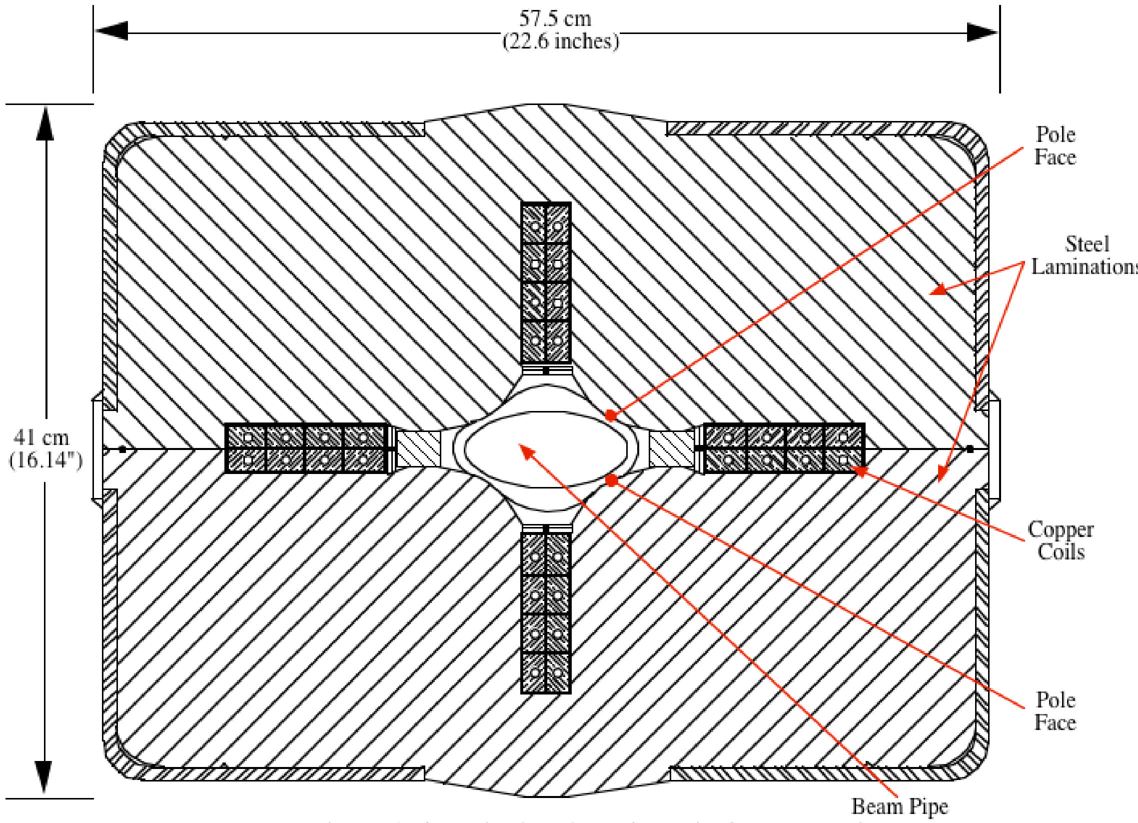
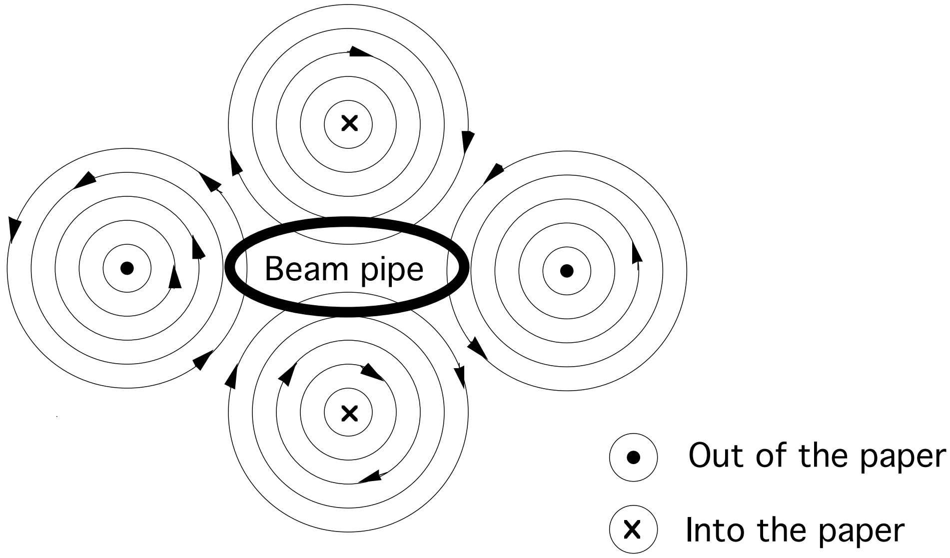


Figure 2-6 Main Quadrupole typical cross-section

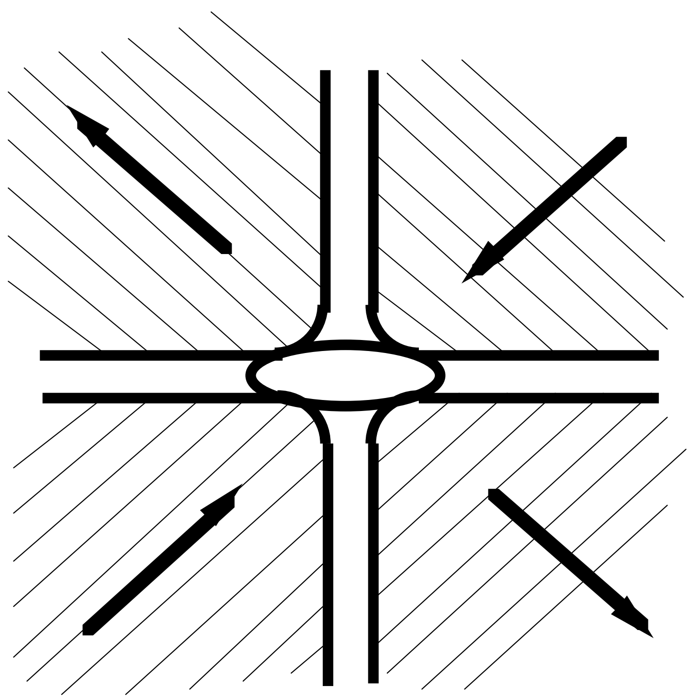
As with the large dipoles, the beam pipe is the elliptical tube in the center. Current passes through the copper coils, square in cross-section, and cooling water passes through the holes in the coils. The steel laminations shape and concentrate the magnetic field.

Quadrupole Fields

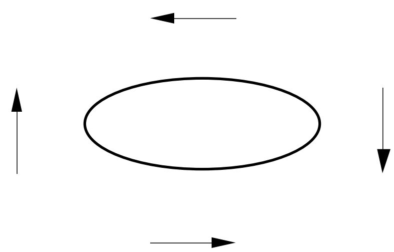
The direction of current in a quadrupole alternates between adjacent poles. For the purpose of discussion, the direction of current in the two side coils can be arbitrarily chosen to be coming out of the paper. In the top and bottom coils current is going into the paper. The direction of the fields can be visualized, as for a dipole, by grasping the coil with the right hand:



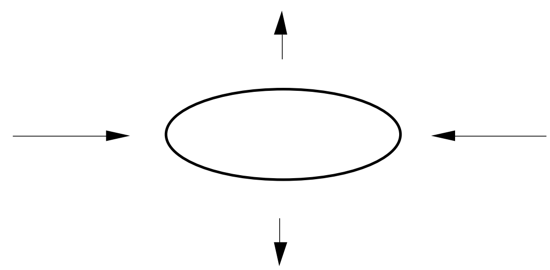
Another look at Fig. 2-6 shows that the iron laminations, also known as pole faces, are designed to capture and shape the field into the four regions between the coils. The predominant directions can be summarized as in the picture on the next page:



The field directions shown above can be resolved into horizontal and vertical components, noticing that the fields are consistently to the left on the top of the magnet, to the right on the bottom, up on the left and down on the right:



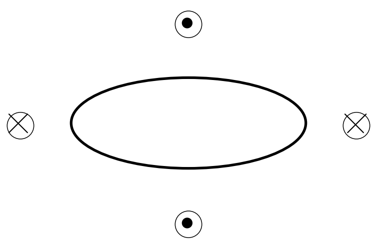
Now apply the right-hand rule to determine the direction of the forces:



The particles on the left will be pushed to the right, and particles on the right will be pushed to the left. A particle at the center will experience no correction (nor should it, since it is at the desired position). This quadrupole is horizontally focusing; horizontally focusing quads are also known as "F" quads.

If the field strength is carefully accounted for along each point on the horizontal axis, it turns out that the restoring force is linearly proportional to the horizontal distance from the center. A particle twice as far from the center will receive twice the correction.

This sounds great, but note that there are also vertical forces present that point away from the center, "defocusing" the beam vertically. These vertical forces are also linearly proportional to the vertical distance from the center.



To keep the beam focused vertically, the next quadrupole in the sequence is connected with the opposite polarity.

The conscientious reader will take out a piece of paper and determine for herself that this quadrupole is vertically focusing. There is a restoring force vertically and a defocusing effect horizontally. Unfortunately, perhaps, this kind of quadrupole is usually referred to by its horizontally defocusing effects and is called a defocusing or "D" quad (not to be confused with the "D" dipoles).

The focusing and defocusing quadrupoles of a given type are identical in construction, but each is connected to a dedicated bus and set of power supplies (Fig. 2-7). Unlike the main dipoles, both leads to the magnet are connected to the same end, and there is no straight-through bus.

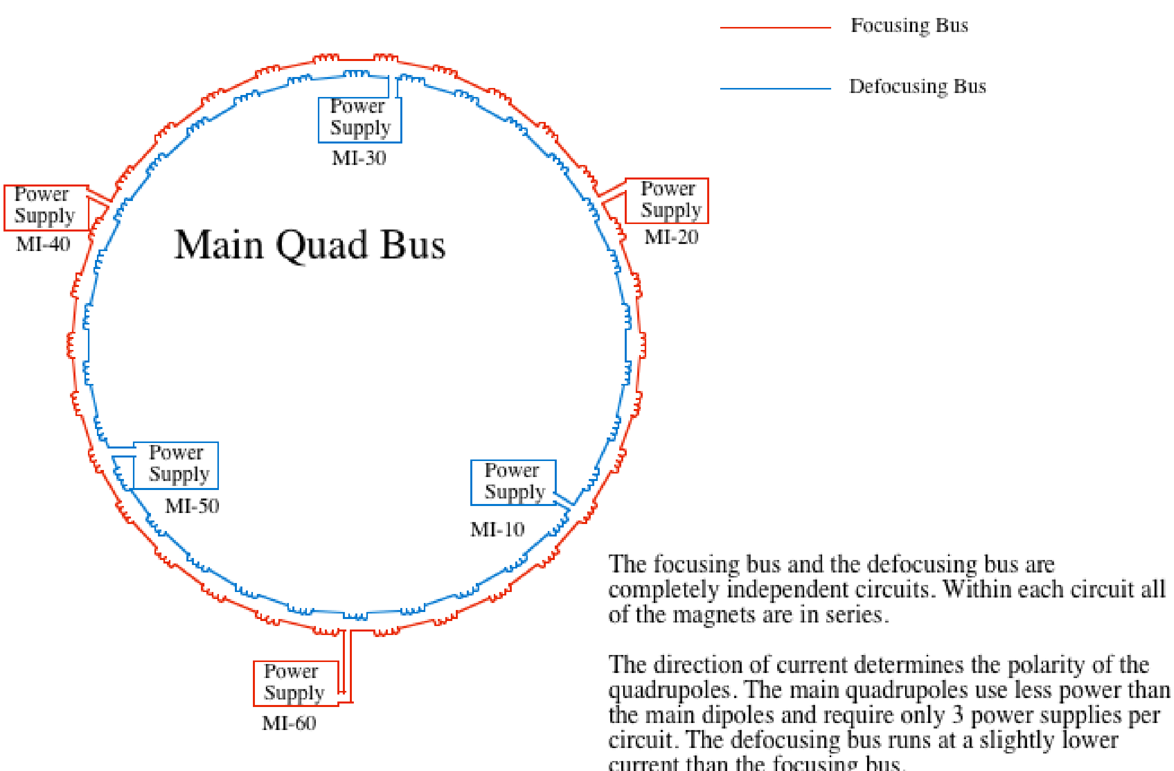


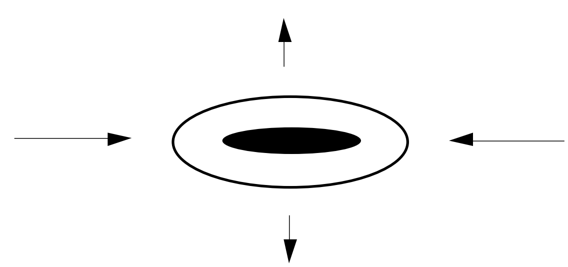
Fig. 2-7

Ring-wide, the current in the focusing bus flows clockwise, while current in the defocusing bus flows counterclockwise. It will be seen shortly that the two currents are not quite the same, but to a first approximation the external magnetic fields are cancelled as they are for the dipoles. The “F” quads are connected to adjacent “F” quads (skipping over the “D” quads between them) and the “D” quads are likewise connected to each other.

The Main Injector Lattice

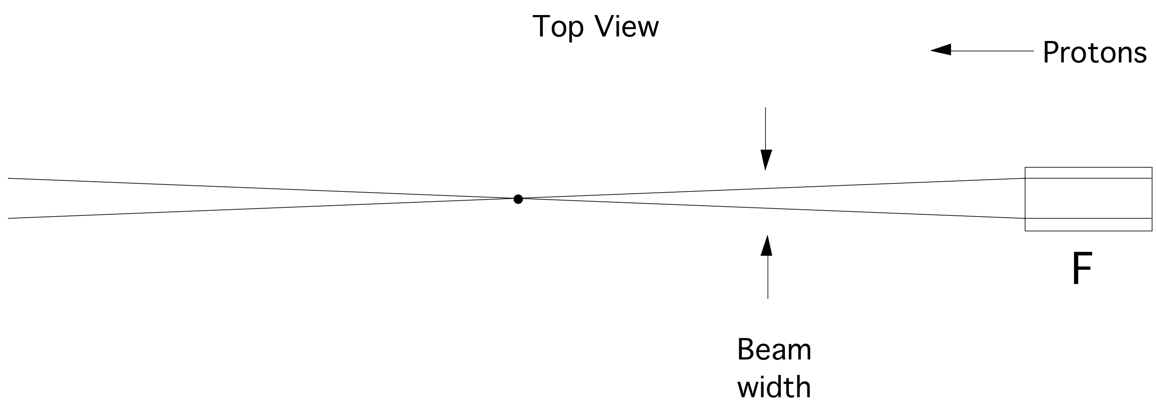
The previous sections in this chapter have described the main quadrupoles and dipoles. To understand the big picture requires some knowledge as to how these magnets are combined to form the lattice. The lattice is intended not as an analogy to the leafy vegetable, but rather to the regular and predictable pattern of atoms in a crystal. The main dipoles and quadrupoles are the “skeleton” around which the other components in the accelerator are arranged. The main quadrupoles actually define the lattice.

As discussed in the last section, there is “F” quads (horizontally focusing) and “D” quads (vertically focusing). The trick now is to space the quads at a distance that minimizes the defocusing effect in both planes. For example, in the “F” quads, the beam distribution looks like this:



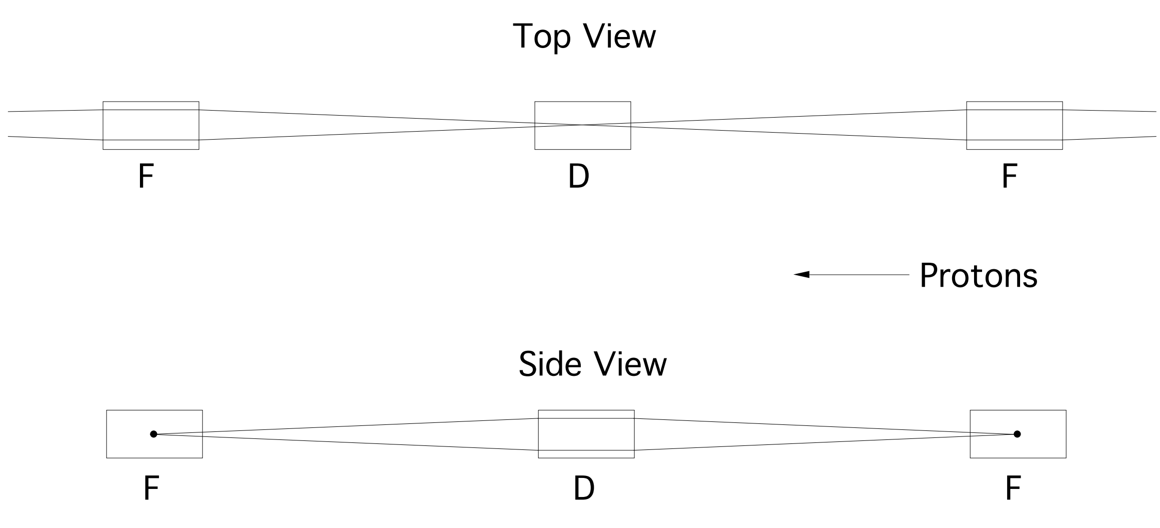
The beam is wide horizontally and narrow vertically. Since the horizontal and vertical forces are proportional to the distance of the particles from the center, the horizontal forces will predominate.

A single quadrupole magnet acts much as an optical lens would, except that focusing only takes place in one plane:



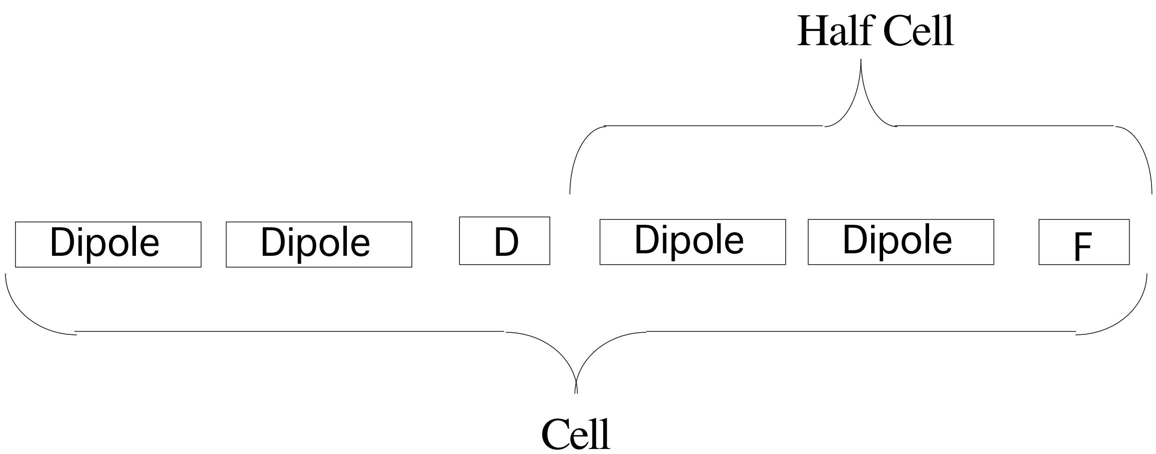
For any given quadrupole, there is only one place at which the beam size is at a minimum, beyond that point it begins to diverge again. In the lattice, the defocusing quads are placed where the horizontal beam size is the smallest, and vertical beam size is the largest; the focusing quads are placed where the horizontal beam size is the largest and vertical beam size is the smallest.

The vertical beam size is one half-cell out of phase with the horizontal:



Again, for both the horizontal and vertical planes, the beam is intercepted and focused where it is the widest. In the Main Injector, the “F” quads and “D” quads alternate, creating what is known as a “FODO” lattice. The “O” designates the drift space between the quads. The drift space is often occupied by dipoles for bending the beam, but other devices or even unadorned beam pipe are valid options.

A typical section of the Main Injector FODO lattice is shown below:



The length of the lattice shown is called a cell. The cell is the basic, repeatable unit of the lattice, in this case the FODO lattice. In this particular cell, each drift space contains two large dipoles. In the arcs between the straight sections, each cell contains six magnets: two quadrupoles and four dipoles. Where the main dipoles are present they are paired “A” and “B” or “C” and “D,” as described earlier. There are no main dipoles in the straight sections (described below), but the number of quadrupoles per cell remains constant.

A half-cell is the distance that includes one quadrupole and the adjacent drift space. A half-cell is not repetitive because the polarity of the quadrupole changes in the next half-cell.

The alert reader will deduce that the longer dipoles will bend the beam in a tighter curve, and that the longer quadrupoles will focus the beam more tightly.

Since there is a main quadrupole at the beginning of every half-cell, and since they alternate between vertically and horizontally focusing quads, the naming convention has been adopted that every focusing location is assigned an even number, and every defocusing location is given an odd number. The other components in the neighborhood of the quadrupole incorporate the number as well, so any component with an even number can usually be assumed to be at a focusing location, and vice-versa.

Straight Sections

The Main Injector ring, as shown in Fig. 2-1, has a shape resembling that of a battered egg. The unevenness is due to the presence of straight sections at 8 locations. The straight sections provide space for specialized functions, usually for beam transfer to or from the Main Injector. Straight sections can be purchased in short, medium, or large sizes.

Even with the odd shape shown in Fig. 2-1, the symmetry of the lattice begins to emerge. The short straight sections at MI-52 and MI-62 (designed for beam transfers to and from the Tevatron, Antiproton Source and Fixed Target experiments) are mirrored by identical short straights at MI-22 and MI-32. The latter two sites were originally included only to preserve the symmetry of the ring, but have now been pressed into service as points of transfer to and from the Recycler. MI-10, a medium-length straight section, is the point where 8 GeV beam enters the machine; its counterpart at MI-40 has been chosen as the location of the abort line. The long straight section at MI-60—a very busy place with multiple beam transfers, the RF accelerating systems, and the extraction line to NuMI—is mirrored by MI-30, which is virtually empty.

It is the location of the straight sections that determines the distribution and strength of the main dipoles and quads. A careful look at Figure 2-1 reveals the two sizes of the magnets and where they are located. The “normal” arcs are comprised of the longer “A” and “B” magnets, shown as dark blue in the diagram. The shorter “C” and “D” magnets, in light blue, act as bridges between the arcs and the straight sections. When traveling through the dipoles the beam is essentially tracing part of a circle.

This arrangement of long and short magnets was made necessary by a phenomenon called dispersion. Dispersion is the tendency for low energy particles to be bent more than high-energy particles as they trace a curve through a dipole. The straight sections are designed as “zero dispersion” regions in which particles are not sorted out by their differences in energy. The “C” and “D” dipoles, and the quadrupoles associated with them, help to ease the beam into and out of the zero dispersion straight sections. The two cells on either side of each straight section are known as “dispersion suppressor” cells:

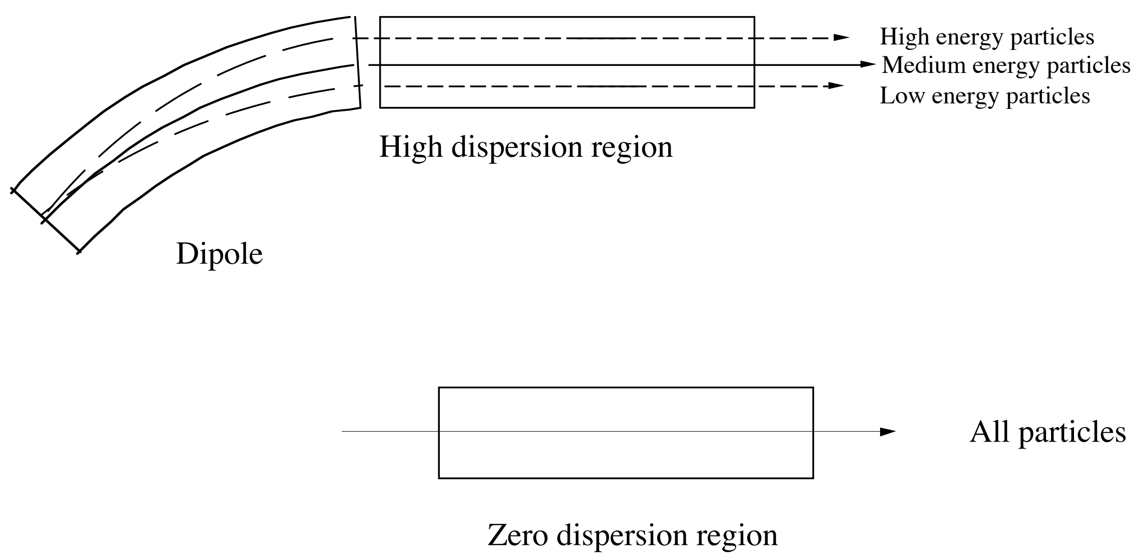


Fig. 2-8 represents the three basic types of straight section in the Main Injector. Fig. 2-8(a) represents the four short straight sections at MI-22, MI-32, MI-52, and MI-62; Fig. 2-8(b) the medium straight sections at MI-10 and MI-40, and Fig. 2-8(c) the long straight sections at MI-30 and MI-60. In each diagram, a part of the normal arc, with its “A” and “B” dipoles, can be seen to either side. Between each pair of dipoles in the normal arcs is an 84” quad. The two dispersion-suppressor cells on either side of the straight section are made up of “C” and “D” dipoles, with 116” quads sandwiched between each pair. The boundary to either side of the dispersion-suppressor region is interfaced with a 100” quad. Within the straight sections themselves, the FODO lattice continues in the form of 84” quads.

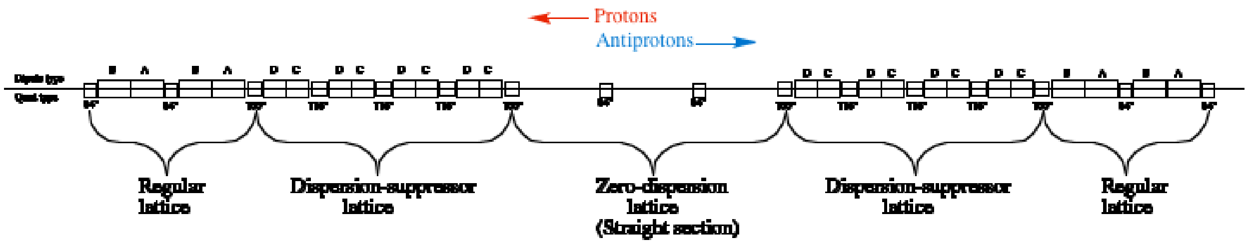


Fig. 2-8(a) Short Straight Sections
MI-22, MI-32, MI-52, MI-62

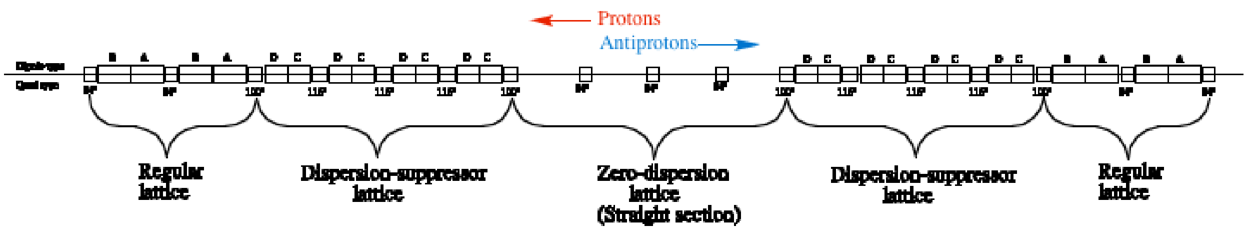


Fig. 2-8(b) Medium Straight Sections
MI-10, MI-40

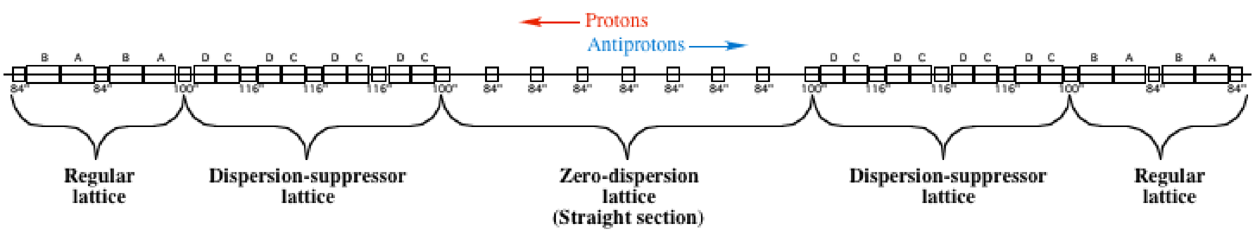


Fig. 2-8(c) Long Straight Sections
MI-30, MI-60

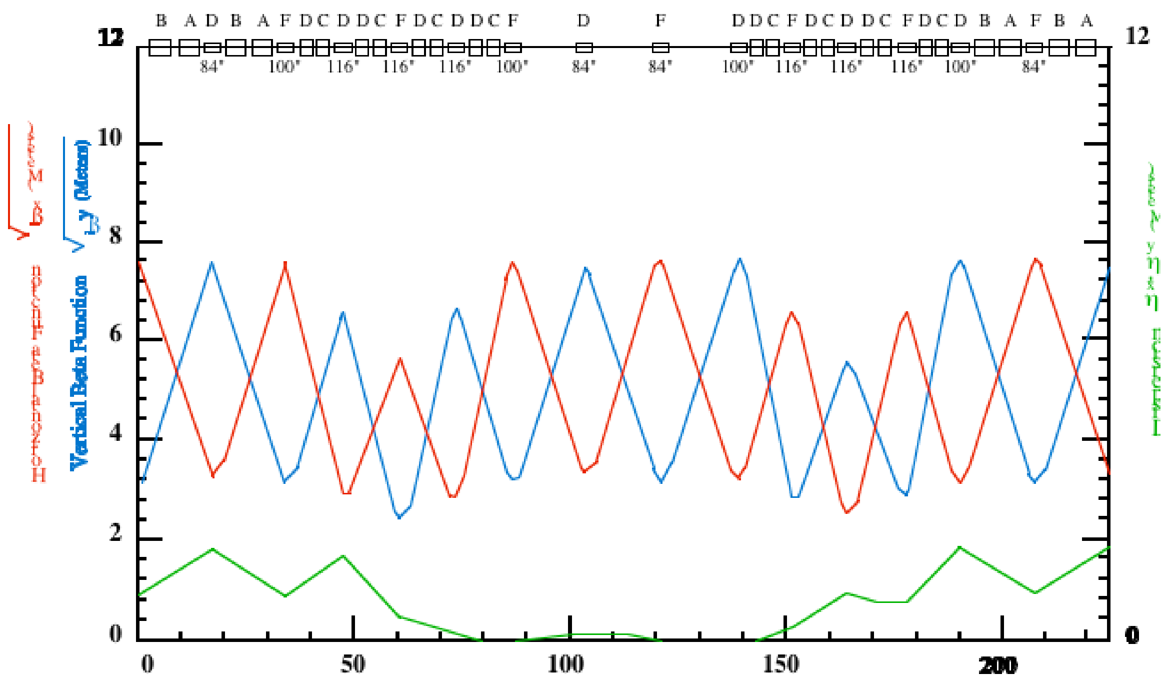
The various quadrupole lengths are necessary to match the changing bend field as the beam enters the zero dispersion areas. The curvature of the normal arcs and the dispersion-suppressor arcs is about the same, although the “C” and “D” dipoles are shorter than the “A” and “B” dipoles, there are more of them over any given length because the cells are shorter. However, the overall focusing strength is greater because all of the quadrupoles in the suppressor arcs are longer than in the normal arcs, and they are closer to each other, and because the cells are shorter. The fact that the ratio of focusing strength to bending strength is larger is what makes the suppressor cells work.

Figs. 2-8 only illustrates the basic lattice of the straight sections; in reality, much of the unused space is filled with magnets and other devices utilized for beam transfer, but the pattern of main dipoles and main quadrupoles does not change.

Just as each straight section has a symmetrically placed partner across the ring, it has an internal symmetry with respect to its own center. (Remember that magnetically there is no difference between magnets of a pair.) Circulating antiprotons are going to see the same sequence of magnetic fields as the protons.

Beta Functions and Tunes

Mathematically, the periodic widening and narrowing of the beam is described by a beta function. The beta function is only one of several lattice functions; dispersion is another. Fig. 2-9 shows the beta functions and dispersion through a typical straight section.



Main Injector lattice functions in the vicinity of a typical straight section; the red and blue traces represent the horizontal and vertical beta functions and the green trace represents the dispersion. The beta functions show that the beam is widest horizontally at the focusing quads and widest vertically at the defocusing quads. The dispersion goes to zero in the straight sections.

The particular lattice shown in the diagram is that of MI-32 or MI-62, but all of the straight sections are similar.

Fig. 2-9 Main Injector Lattice Functions

The location of the straight section itself, occupying the center third or so of the diagram, can be recognized by the zero dispersion.

The beta functions in this diagram for both the vertical and horizontal planes are superimposed on each other; remember that the horizontally the beam is widest at the “F” quads and the vertically it is widest at the “D” quads.

Beam width is intuitively a straightforward concept, but quantitatively it is rather complex. Notice that the vertical axis is labeled with $\sqrt{\beta_x}$ and $\sqrt{\beta_y}$, which are actually the square roots of the horizontal and vertical beta functions. These terms require about 20 years of graduate school to understand; let it suffice for now to say that the bigger the beta function, the wider the beam.

It would be logical to assume that the individual particles oscillate in exactly the same manner as the beta function. That assumption would be incorrect. Within the beam envelope, defined by the square root of the beta function, individual particles undergo an oscillation that is about four times slower than that of the beta function. The slower motions are known as betatron oscillations. Getting confused yet? The apparent discrepancy comes from the fact that the individual particles are not obliged to all start out with the same position and angle of deflection; the billions and billions of particles in each bunch each have their own trajectory. The beam envelope of the beta function defines the outer limits of all their motions.

Any given particle, as it moves through the quadrupoles of the lattice, is unlikely to be exactly on the desired orbit; it will be somewhat off-center horizontally and vertically. In either plane, as it receives a restoring force from a quadrupole, it receives a push toward the desired orbit position. It will then continue to drift past the desired position until it is on the opposite side of where it started. Its next encounter with a quadrupole of the proper polarity will push it back toward the desired position. It continues oscillating back and forth around the desired orbit as long as it remains circulating in the machine. This progression, which resembles a bumpy sine wave as the particle moves through the lattice, is referred to as phase advance; the Main Injector lattice is designed with a phase advance of about 90 degrees per cell. A particle returns to its original phase after traversing about four cells. If the field in the quadrupoles is strengthened, the oscillations are faster and take place over a shorter distance. The total number of betatron oscillations in a single revolution of the beam is called the tune, defined separately for the horizontal and vertical planes. Increasing the tune is equivalent to increasing the amount of current in the quadrupoles.

There are 104 cells altogether in the Main Injector ring: 104/4 = 26, so one would expect the tunes in Main Injector to be 26. In actuality, the Main Injector was designed for a horizontal tune of 26.425 and a vertical tune of 25.415. (The fact that the vertical tune is lower than the horizontal tune means that the current in the vertical bus is lower than the current in the horizontal bus.) If an exact integer tune were selected, a given particle would see the same tiny field errors once every revolution; these errors would quickly add up and the motion of the particle would become unstable. The same is true of half-integer tunes, say, 26.5, where the particle would see the same errors every other revolution. In fact, several easily visualized fractions, known as resonances, must be avoided if beam is to stay in the accelerator. Applications programs are available to adjust the current in each of the two quad busses to optimize the tunes; more about these in the chapter on power supplies.

During resonant extraction to fixed target experiments, the tunes are deliberately pushed toward a resonance in order to cause them to leave the machine in a controlled way. Perhaps someday there will be a chapter on resonant extraction.

A more general and mathematical treatment of tunes can be found in the “Concepts” book. Of particular relevance here are the chapters on “Beam Characteristics” and “The Lattice.”

Corrector Dipoles

The main dipole magnets carry the lion's share of the work at keeping the beam on the correct orbit within the beam pipe. They are all in series with each other, tied to the same set of power supplies, and have identical currents at any given instant. However, no accelerator is perfect, and it is inevitable that numerous local adjustments will be needed due to the small differences in the construction of the individual magnets. The correction dipoles are puny compared to their multi-ton counterparts; the horizontal correctors weigh only 321 pounds apiece. The advantage to using them is that each one is individually controllable. They come in horizontal and vertical flavors.

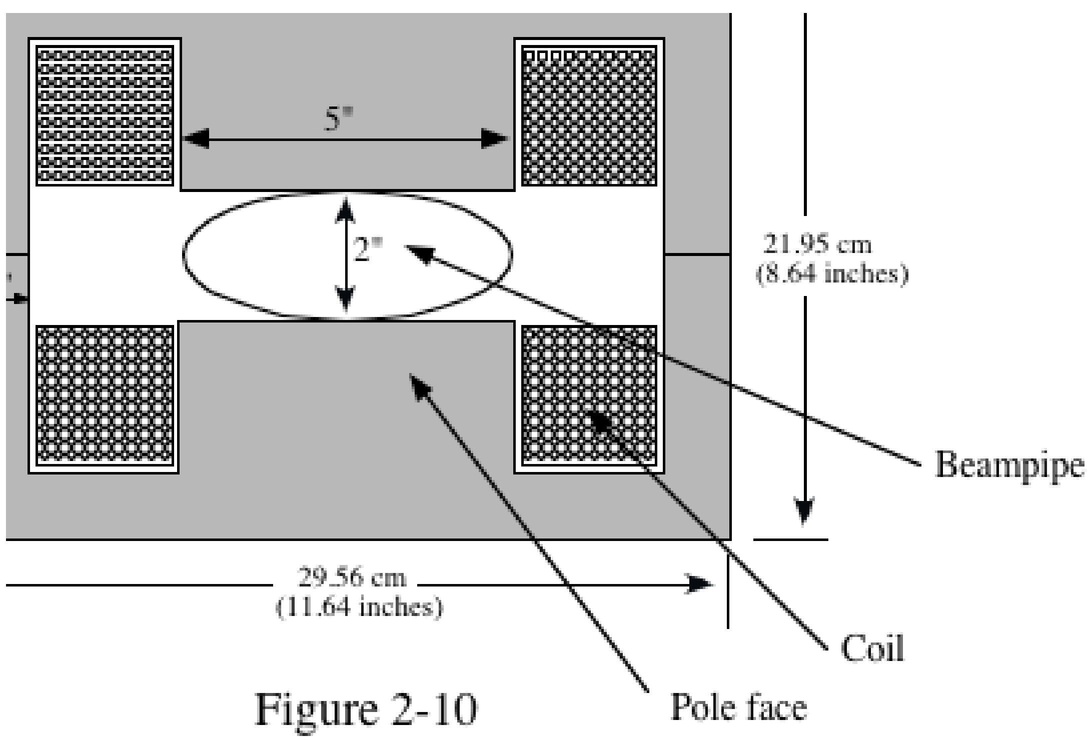


Figure 2-10
Horizontal Corrector Dipole

The horizontal correctors are just under 9" high and 12" wide, and are 17" long (Fig. 2-10). Like the large dipoles, the field originates in the coil current; unlike the large dipoles, the coils are formed from 400 turns of relatively thin (#10) wire. The top and bottom halves of the magnet are fabricated separately and must be bolted together around the beam pipe in the tunnel.

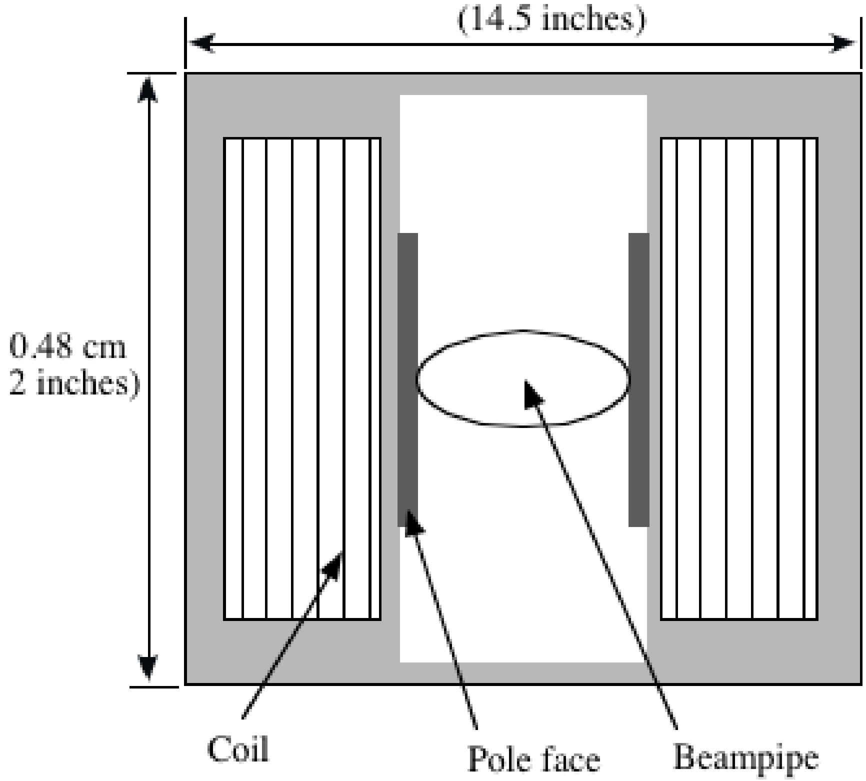


Figure 2-11
Vertical Corrector Dipole

The vertical corrector dipoles, since the field itself is horizontal, require that the left and right halves be built separately and then bolted together downstairs (Fig. 2-11).

Normally, there is a horizontal corrector dipole in front of each main focusing quadrupole and a vertical corrector in front of each main defocusing quadrupole, although there are occasional exceptions in the straight sections. Remember that beam is widest horizontally at the focusing locations and widest vertically at the defocusing locations. Changing the current in, say, a horizontal magnet will have the greatest effect on beam losses at the next horizontal magnet, where the lever arm is the greatest; the chances of scraping beam against the beam pipe is also the highest because of the beam size.

In practice, most changes to the corrector magnets come in the form of 3-bumps. A 3-bump is typed into a parameter page and knobbed. The upstream magnet changes the position of the beam at the point where losses are high, and then the magnet at the point of interest bends the beam in the opposite direction to get it back to its original position. Finally, the downstream magnet bends the beam to adjust the angle. If done properly, the bump is completely “local” and does not change the orbit at any other point in the ring. This miracle usually works because the software on board the parameter page knows the phase advance between the correctors, and can calculate the needed currents.

Skew Quadrupoles

There are 16 skew quadrupoles in the Main Injector (Figs. 2-12, 2-19). Their purpose is to control the amount of coupling between the vertical and horizontal tunes. When the tunes are coupled, any attempt to change the horizontal tune will also affect the vertical tune, and vice-versa. Reducing the coupling allows the tunes to be adjusted more independently.

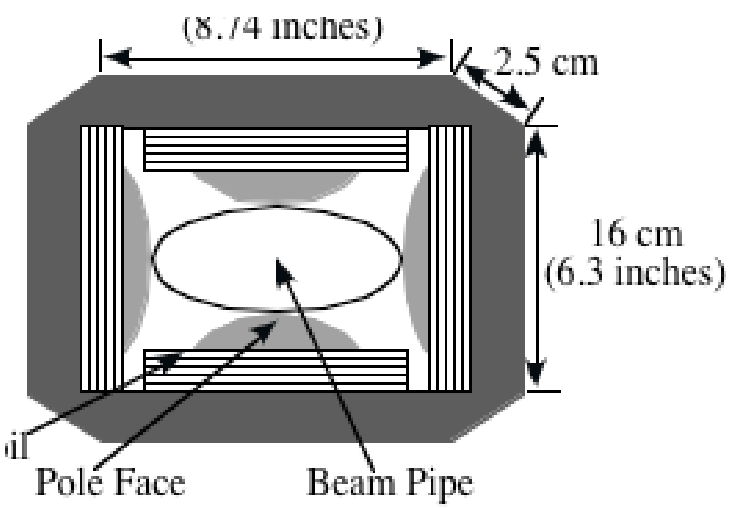


Figure 2-12
Skew quad

Unlike the other quads, both large and small, the pole faces have been rotated by 45° so that they are parallel to the horizontal and vertical planes; the skew quads look “normal” and the “normal” quads look skewed. They are distributed evenly between focusing and defocusing locations (Fig. 2-20), and clustered into four groups of four.

Trim Quadrupoles

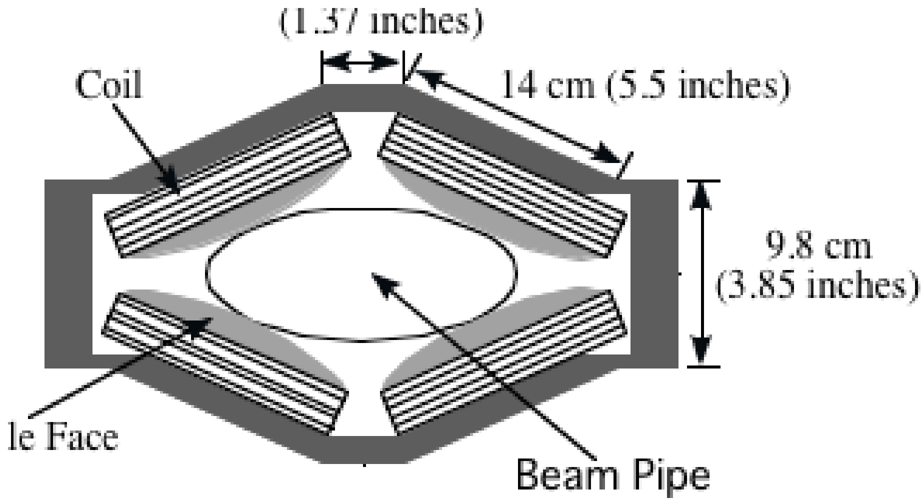


Figure 2-13
Trim Quad

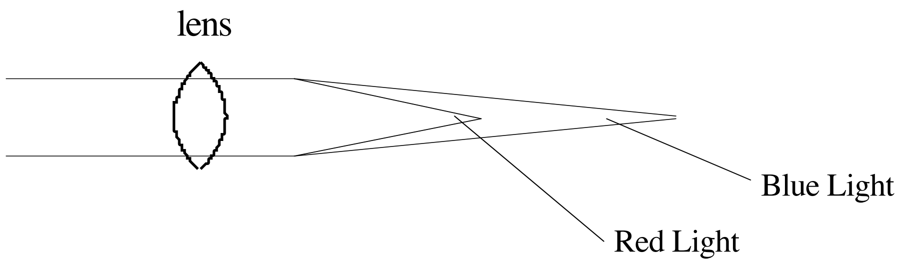
There are also 16 trim quadrupoles in the Main Injector (Figs. 2-13, 2-21). Unlike the magnets already discussed, they all focus in the horizontal plane only. They are used during resonant extraction, which is a process that affects the beam horizontally. They can also be used as harmonic correctors, available for adjusting specific characteristics of the betatron oscillations, such as phase advance.

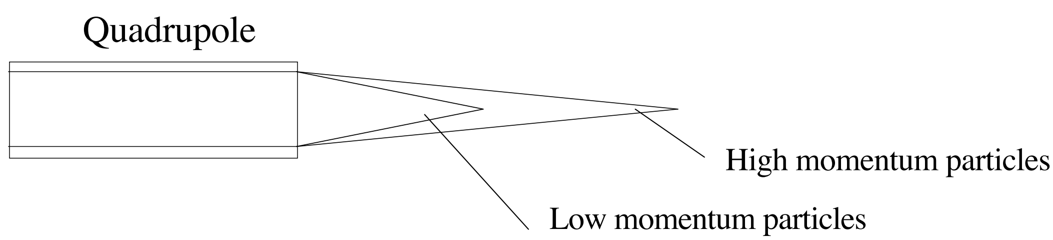
The trim quadrupoles are recycled from the Main Ring. The poles are oriented at 45˚ to the horizontal and vertical axes, as with the large quadrupoles. They are, along with the skew quads described above, among the smallest magnets to be found in the Main Injector. Like the horizontal correction dipoles and the skew quads, the top and bottom halves must be bolted together around the beam pipe. Like the skew quads, they are clustered into four groups of four.

The role of the trim quadrupoles in manipulating the beam will be discussed in the hypothetical chapter on resonant extraction.

Sextupoles

Sextupoles, which by definition have six poles, are used to control a phenomenon called chromaticity. The word for “chromaticity” is related to the word for “color,” and is used in optics to describe lenses for different wavelengths of light that have different focal lengths, as in the picture below.





The separation of colors occurs because blue light has more energy than red light and is therefore more difficult to bend.

The concept of chromaticity in accelerators is intended as an analogy to what happens in optical systems. Just as light comes in a variety of energies, a group of particles in an accelerator has a range of energies. (Since accelerator physicists often speak of momentum rather than energy—momentum is the kinetic energy of a particle added to its rest mass—momentum will be used rather than energy in following discussion. The momentum of particles traveling at relativistic speeds is expressed in units of GeV/c; quantitatively, the numbers come out as the kinetic energy of the particle (in eV) plus the rest mass of the particle. The rest mass of a proton or antiproton is about 938 MeV.) Because the RF concentrates the beam in bunches, the range in momentum is fairly small: dp/p, which is the range in momentum spread divided by the total momentum, tends to be near 10^{-3}. Nevertheless, if an accelerator has significant chromaticity, even that level of momentum spread will create problems with the tune. Higher momentum particles, being harder to bend, will have longer focal lengths as they go through the quads, and will have a lower tune because they undergo fewer oscillations per revolution. A certain tune spread is acceptable, but if the tune spread gets to be too large some of the particles will begin to approach a resonance and they will be lost from the machine.

The equation defining chromaticity is:

$$\frac{\Delta \nu}{\nu} = \xi \frac{\Delta p}{p},$$

where ν is the tune, ξ is the chromaticity, and p is the momentum. In other words, the tune spread is proportional to the momentum spread; the chromaticity is the constant of proportionality.

A sextupole magnet (Fig. 2-14) compensates for the chromaticity by applying different forces to particles of different momenta, so that the

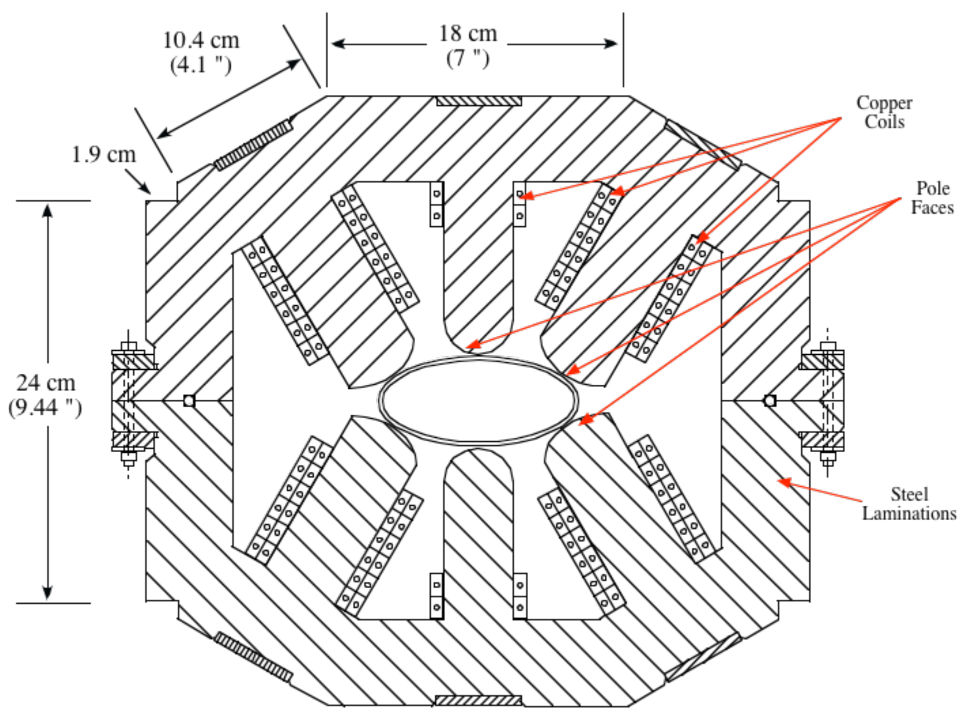
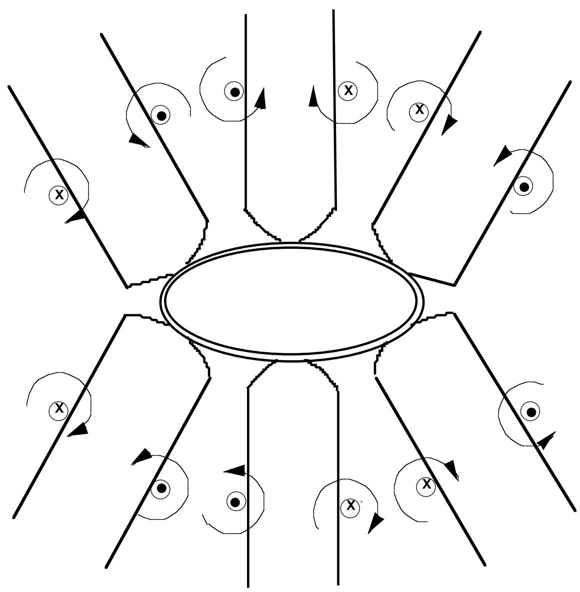


Figure 2-14 Cross-Section of Main Injector Sextupole

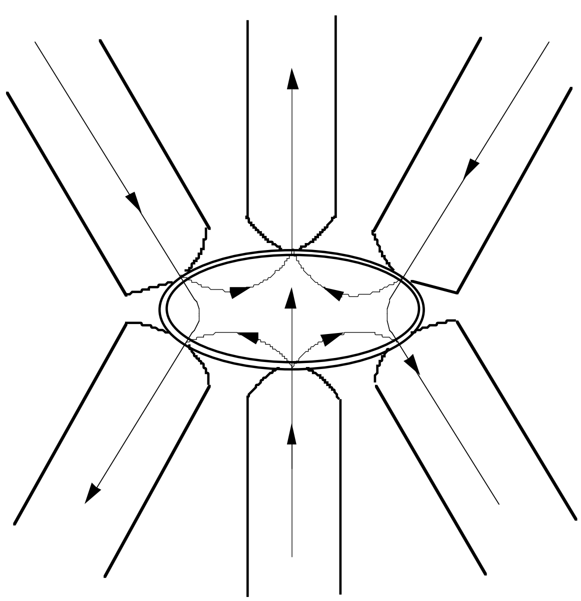
variation in focal length, and therefore the variation in tune, can be controlled.

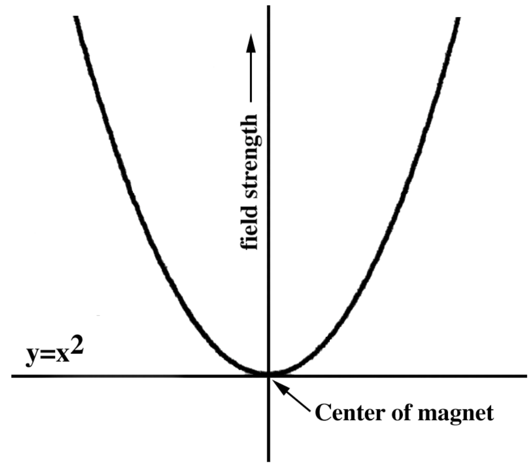
A copper coil accompanies each pole face, the coils appearing as pairs in cross-section. As with the other magnets, the current in the coils magnetizes the steel pole faces; the steel concentrates and shapes the field.

The current flowing in a horizontally focusing sextupole looks something like this in cross-section below.



The direction of each field in each pole face is either toward the beam pipe or away from it, and can be summarized by the picture below.

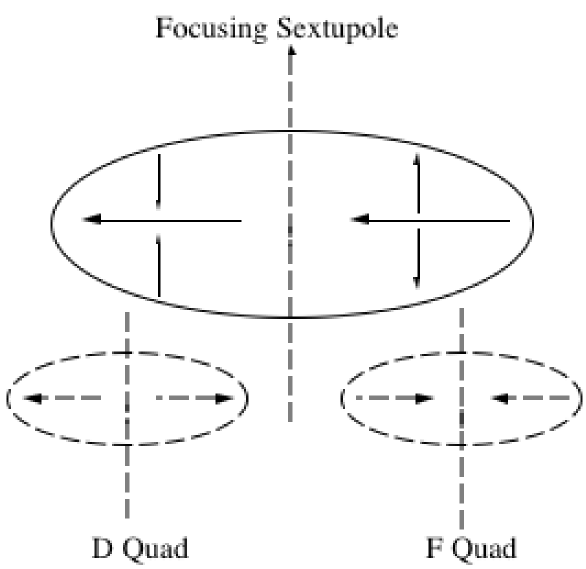




When the right-hand rule is applied and the restoring force is plotted as a function of the distance from the center, a parabola results:

Algebraically, a parabola is expressed as $y = ax^2$, where "a" is a constant. The x^2 term is the reason that sextupoles are considered "second-order" components. The parabola is always positive, except at the center, where it is zero.

The result is at first startling to those used to the symmetry of quadrupoles, because, being always positive, the horizontal forces are all in the same direction. Moreover, because the top and bottom coils combine to produce a field that opposes that of the "side" poles, the field vanishes at the center of the magnet.



So how does this unidirectional parabolic field differentially focus particles of different energies? If a vertical line is drawn through the center of a horizontally focusing sextupole, the fields of the outside half are in the same direction as those of a horizontally focusing quad, and those of the inside half are in the same direction as those of a horizontally defocusing quad, as shown on the left.

Because of the dispersion created by the dipoles, higher energy particles will tend to be toward the outside of the beam path, and lower energy particles toward the inside (except, obviously, in the zero-dispersion regions.) Fortunately, it is the higher energy particles that need the extra focusing, because of their longer focal lengths; the low energy particles have a focal length that is too short, and being on the outside, the defocusing force undoes a portion of the quad focusing.

There are no sextupoles located in the straight sections or the dispersion-suppressor cells, because without dispersion they are of no use (see Figs. 2-22, 2-23).

Taken in combination, these effects narrow the tune spread to an acceptable range. Notice that the momentum spread of the beam has not been changed; it has just been managed so that beam is not lost from the machine.

In addition to the chromaticity sextupoles described above, there were trim sextupoles and skew sextupoles in the Main Ring. These have been salvaged and the option remains to use them in the Main Injector as harmonic correctors if deemed necessary.

The safe sextupoles are not used in the Main Injector.

Octupoles

A cross-section of a Main Injector octupole—yes, you can figure out the number of poles—is shown in Fig. 2-15. Octupoles are like sextupoles insofar as they selectively focus particles, and that they use the dispersion of the beam to identify those particles; they are like the quadrupoles in that the direction of the force changes when crossing the center of the magnet. They are unique in being able to preferentially focus particles with high amplitudes of

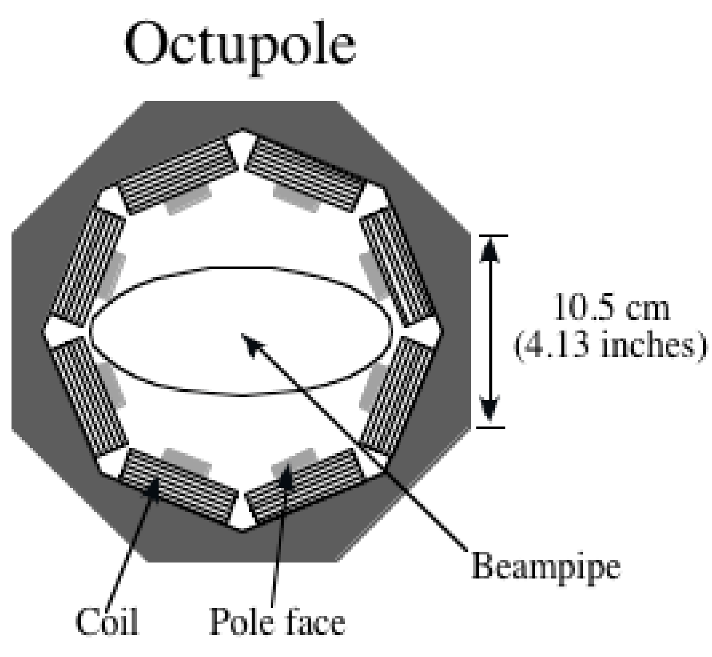
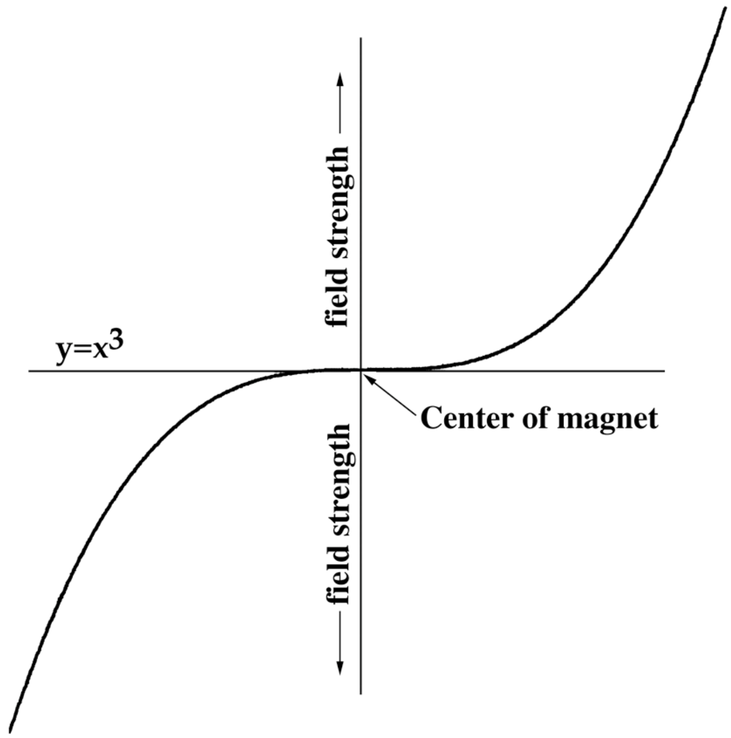


Figure 2-15



betatron motion. Amplitude is strictly a transverse motion and is not the same as the longitudinal momentum spread dealt with by the sextupoles. (I agree, this is becoming more difficult to visualize with every step.) Octupoles are “third-order” components, and the force obeys equations such as $F=ax^3$, as in the graph on the next page:

In a cubic equation like this, the force increases very sharply with increasing distance from the center. It is clear from the curve that a particle farther from the center will see a much larger restoring force, raising its tune.

There are vertical and horizontal octupoles in the Main Injector, and they have a relatively modest role in maintaining circulating beam. Part of their function is to compensate for octupole components generated by the shape of the laminations in the 84” quadrupoles recycled from the Main Ring. (The laminations had been deliberately trimmed in ancient times in order to push the Main Ring beam to higher energies.)

The horizontal octupoles greatly outnumber the vertical octupoles, because they are used during resonant extraction. Their role will be discussed in that chapter.

Permanent Magnets

As far as the Main Injector is concerned, permanent magnets are only used in the MI-8 line and beam transfer to and from the Recycler. If the reader is already saturated with the study of magnetic fields at this point, he/she may skip this section, and the loss of continuity will not be noticed until Chapter 7 is encountered. It would, however, be wise to read the "Names and Locations" section at the end of this chapter.

The extensive use of permanent magnets is new to accelerator design. In the Main Injector, permanent magnets make up most of the MI-8 line; the Recycler, of course, is built almost entirely of permanent magnets. Because their magnetic field strength cannot be changed at a whim from the control room, permanent magnets are only used where the beam energy does not change.

In recent years, an industry has developed for the production of strontium ferrite magnets. Strontium ferrite is the material of choice for a wide variety of applications, from magnets on refrigerator doors to inductive pickups in automobiles. Fermilab contracted with industrial suppliers of strontium ferrite to make tens of thousands of ferrite bricks. In the factory, the strontium ferrite is pulverized and compressed into a brick. Each brick spends several days slowly creeping through a 300-foot kiln until the ferrite has been baked into a ceramic.

Fermilab places the bricks in an Accumulator-style dipole that magnetizes them; the dipole is pulsed for about 3 seconds and the brick retains a field. (Although hysteresis is a nuisance in electromagnets, it is actually responsible for the "permanence" of a permanent magnet. Remember that once the magnetic domains are aligned, there is a self-sustaining field that keeps them aligned.) The bricks have a dull gray color and are predictably heavy.

The process of assembling the bricks is surprisingly empirical and, at first glance, imprecise. They are stacked around a section of beam pipe and, if field measurements do not meet specifications, they can be restacked. The assembly of bricks is enclosed in a long steel box. The ferrite bricks play the same role as the copper coils in the electromagnets, creating the magnetic field; the steel box is analogous to the steel laminations of the magnets, strengthening the field. Steel pole faces internal to the casing strengthen and shape the field.

The magnetic field is susceptible to changes in temperature, so temperature compensation shims are sandwiched between the bricks as necessary. The shims are made of an iron-nickel alloy, probably melted down from a meteorite; the alloy has a Curie point (demagnetization temperature) of 50˚C. The weakening of the field in the shims, as the magnet gets warmer, compensates for the field changes in the ferrite bricks. After assembly, the entire magnet is “frozen” to 0˚C for 24 hours to standardize the hysteresis due to thermal cycling. As the magnet warms back up to room temperature, the field is monitored in order to verify the effectiveness of the temperature compensation shims.

Adding a geometrically complex end shim at either end can compensate for higher order components of the field. A variety of end shims are kept on hand, and a computer matches the optimal pole face to the measured field. (This is analogous to the role that the end packs play in the main dipoles.)

Permanent magnets come in several varieties. Horizontal dipoles are used in the MI-8 line. However, permanent magnet quadrupoles are used sparingly, because gradient magnets, similar in concept to the combined-function gradient magnets in the Booster, do most of the focusing.

All of the dipole magnets are identical in cross-section (Fig. 2-16). In the MI-8 line, the horizontally bending dipoles are referred to as PDD

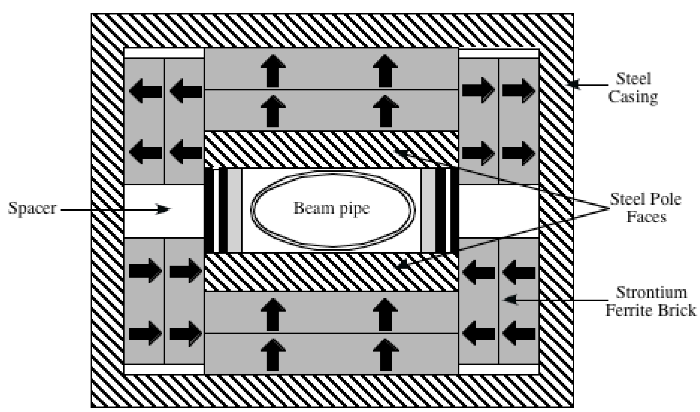


Figure 2-16
PDD Dipole

PDD stands for "Permanent Double Dipole." The ellipse in the center is the beam pipe. The gray rectangles represent the permanently magnetized strontium ferrite bricks; the arrows represent the direction of the magnetic field. The "Double" designation refers to the fact that the bricks are stacked two layers deep. The steel in the casing and the pole faces are of a low carbon type that can retain magnetic flux.

You can find PDD magnets in the MI-8 Line. Refer to Figs. 7-1, 7-2, and 7-4 to see how they are distributed in the line.

magnets, the "P" standing for "permanent" and the "DD" standing for "double dipole." "Double dipole" comes from the fact that there are two layers of ferrite brick in the magnet. Stacking the bricks in two layers allows for a shorter magnet length than would otherwise be the case.

The strength of the field is inversely proportional to the distance between the two steel pole faces; aluminum spacers allow the field to be weakened or strengthened as necessary.

Notice that the field lines in Fig. 2-16 point up in the region of the beam pipe, which is opposite the direction of the field in the Main Injector dipoles. The beam in the MI-8 line is normally bent to the right, rather than to the left as in the Main Injector ring. (The MI-8 line does have a short stretch, called the Reverse Bending section, in which beam needs to be bent to the left; this is accomplished by turning the PDD magnets upside down.)

A cross-section of a typical permanent quadrupole magnet (PQP) is shown in Fig. 2-17. A focusing PQP can be converted into a defocusing quad by turning it 180˚ around its vertical axis, or by rotating it 90˚ with respect to its longitudinal axis. Minor adjustments to the field are accomplished by adding steel washers (developed by elite units of the Ace Hardware Research Division) to the corners of the magnets. The only PQP magnets used in the Main Injector are in the Reverse Bending section.

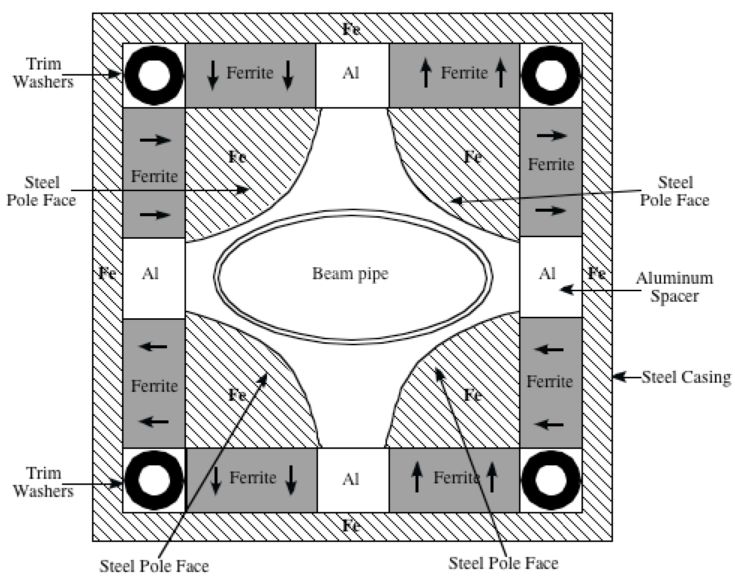


Figure 2-17
PQP Quadrupole

The PQP permanent quadrupoles are used in the Reverse Bending Section of the MI-8 Line. Permanently magnetized strontium ferrite bricks drive the magnetic field, which is shaped and reinforced by the iron pole faces. Trim washers are added for fine adjustments to the fields.

See Figs. 7-1 and 7-3 for the distribution of the PQP magnets in the MI-8 line.

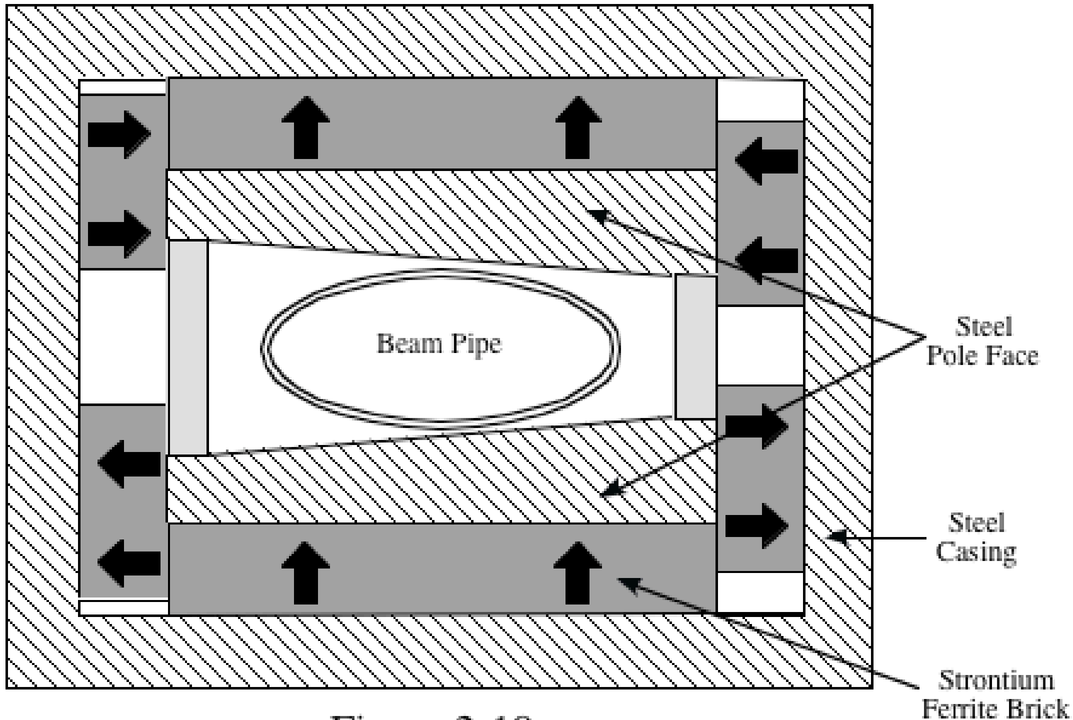


Figure 2-18
PGD Gradient Magnet

PGD stands for "Permanent Gradient Dipole." Like the Booster gradient magnets, PGD magnets can be thought of as having both dipole and quadrupole components. The slope of the iron pole faces above and below the elliptical beam pipe creates the gradient.

PGD magnets are used in the MI-8 line. See Figs. 7-1, 7-4, and 7-5 for their distribution.

A majority of magnets in the MI-8 line and the Recycler are the PGD (permanent gradient dipole) magnets (Fig. 2-18). The PGD magnets are similar in principle to the combined-function gradient magnets of the Booster. They are built to have both dipole and quadrupole field components. The shape of the pole faces, which are slanted in a linear fashion, generates the quadrupole components of the field.

More details on the use of permanent magnets in the Main Injector can be found in the “Beam Transport Lines” chapter.

Names and Locations

It is now possible to assemble an integrated view of the distribution and naming of the magnets responsible for maintaining circulating beam in the Main Injector.

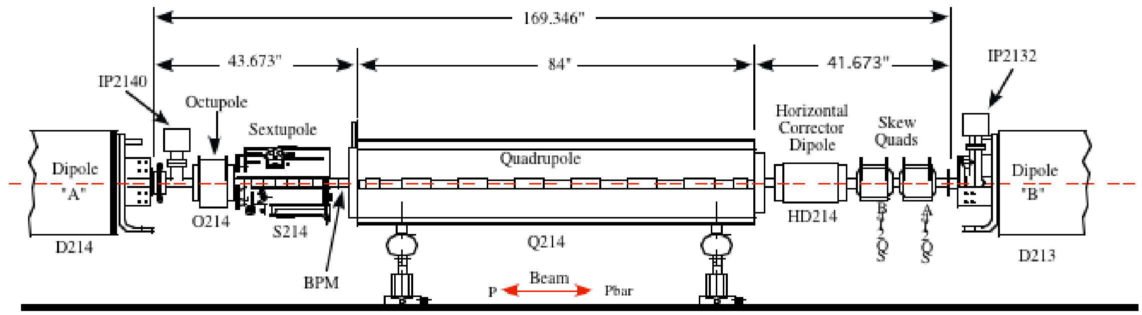
The naming system is anchored around the main quadrupoles. Each quadrupole is assigned a number, and each device near the quadrupole includes that number as part of its name.

Since beam first enters the machine at MI-10, the numbering scheme is defined to start at the beginning of that straight section. The first series of numbers, from MI-10 to MI-20, begins with the "100" location at the first quadrupole (proton direction) in the straight section. Between MI-10 and MI-20 the number increments with each main quadrupole. The "100" location is occupied by a focusing quadrupole; the convention has been adopted that focusing locations be assigned even numbers, with the defocusing locations getting the leftovers.

When the MI-20 Service Building is reached, the "200" series begins. This series begins with "201" because there is a defocusing quadrupole at that location.

The "300" series begins with the straight section at MI-30. Again, whenever a straight section is present at a service building, the new series of numbers begins at the first quadrupole of the straight section. The rest of the pattern should be clear (review Fig. 2-1). Unfortunately, for those who have to remember such things, the number of locations is not consistent from section to section; it can be 31, 32, or 41.

Magnets and other components near the large quadrupoles are assigned a name based on the quadrupole number. Fig. 2-19 shows the layout of the magnets at a selected location.



The correction magnets at any given location are clustered around the main quadrupole, and take on the number of that quadrupole. The name of the quadrupole itself starts with "Q." The sextupole and octupole magnets, which are generally downstream of the main quadrupole, are prefaced with "S" and "O," respectively. The corrector dipoles are prefaced with "HD" or "VD." The main dipoles are designated by "D." The two main dipoles downstream of the main quadrupole take the number of the main quad, but main dipoles upstream take the preceding number.

If there is more than one corrector of the same type, such as the two skew quads at this location, they are designated "A and "B."

Ion pumps have a 0, 1, or 2 linked to the location number. In this picture, the first Ion pump at Location 214 is IP2140; IP2141 is between the "A" and "B" dipole, to the left of the picture. IP2132, at the right of the picture, is the last pump belonging to location 213.

Compare the correctors in this picture to Figs. 20-25. Different combinations of correctors are found at different locations.

Fig. 2-19
The 214 Girder: Typical Magnet Locations and Naming Conventions.

This particular combination of magnets can be found at the 214, 336, 514, or 636 locations. Suppose that it represents the location at 214. The quadrupole itself is given the name “Q214.” The two large dipoles downstream (proton direction) also belong to this location, and are given the names “D2141” and “D2142,” in that order.

The magnets immediately upstream of the large quadrupole, up to the previous main dipole, also belong to this location. The main dipoles upstream belong to the “213” location. If an ion pump (responsible for maintaining vacuum) is upstream of the main quadrupole, it takes the name of the previous location.

Preceding (proton direction) every large quadrupole is a correction dipole: a horizontally bending dipole at the focusing locations, or a vertically bending dipole at the defocusing locations. The horizontal dipole at the 214 location is named “H214,” as the vertical corrector at the previous location is named “V213.”

The skew quads, 16 in all, are grouped into four clusters (Fig. 2-20). At the “x14” and “x36” locations, there are two skew quads on the same girder. The skew quads at location 214 are named “SQ214A” and “SQ214B,” in that order (proton direction). As mentioned earlier, the skew quads are divided equally between the horizontal and vertical locations. The other two skew quads in this cluster are SQ213 and SQ215.

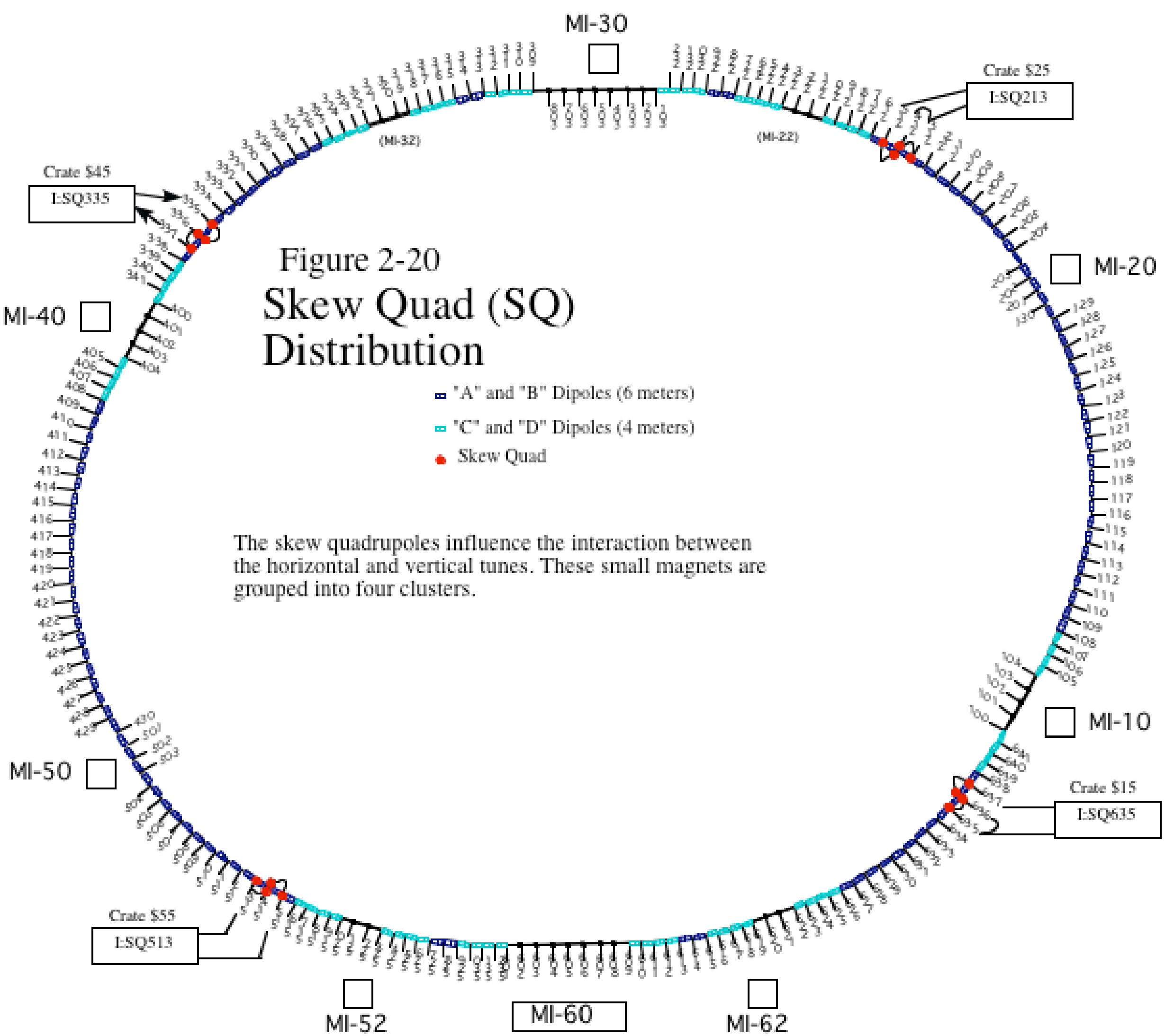
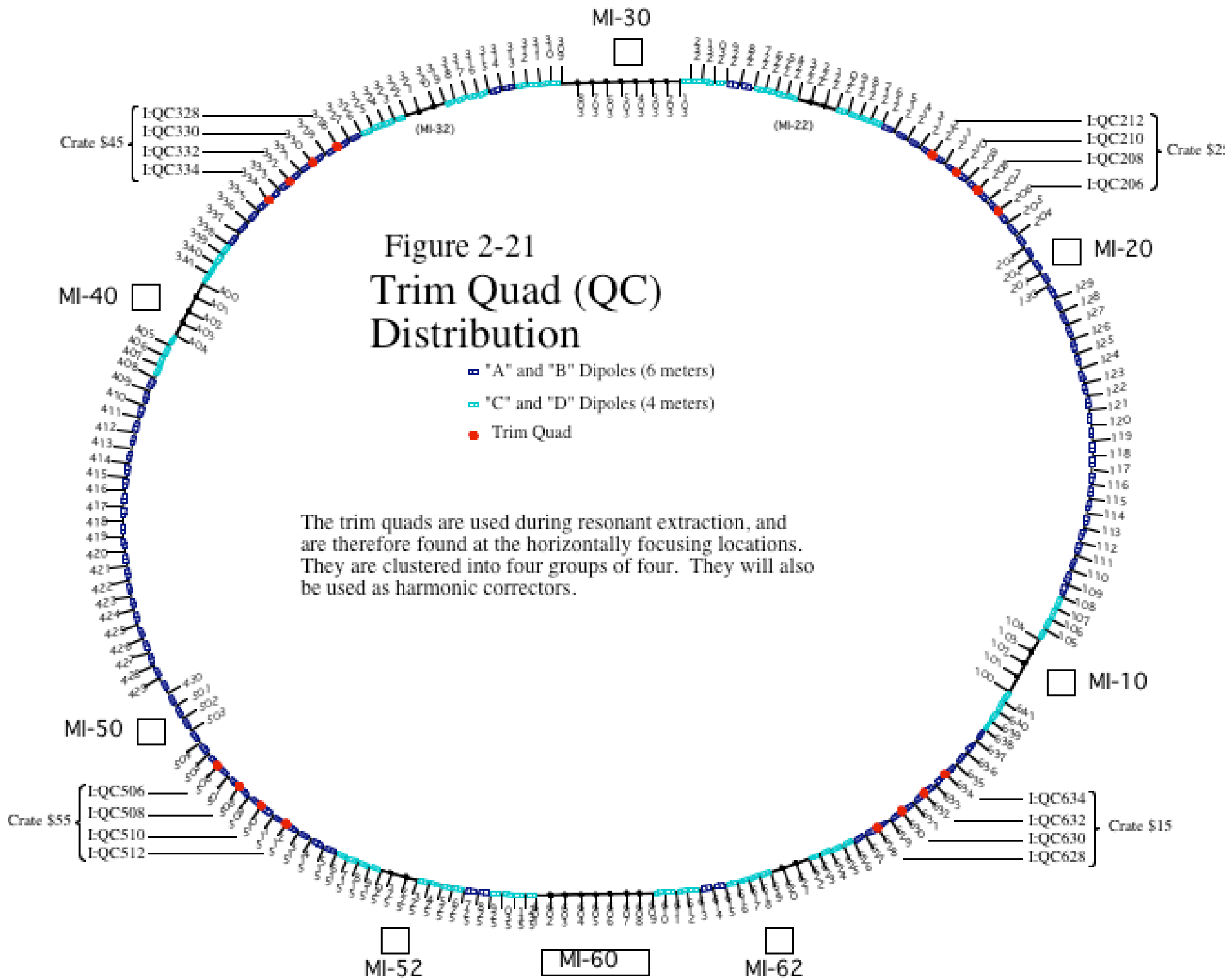
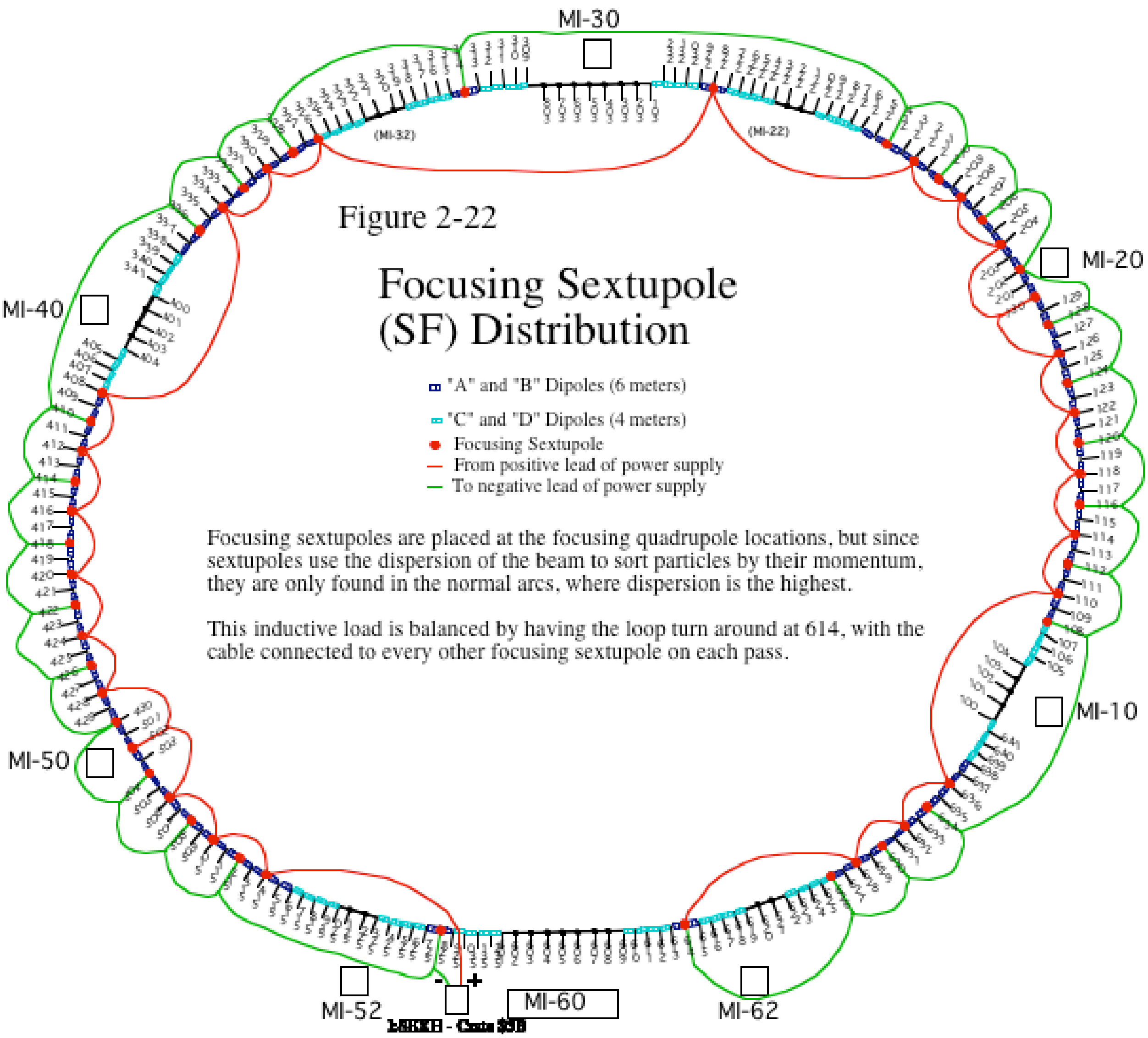


Figure 2-20
Skew Quad (SQ) Distribution

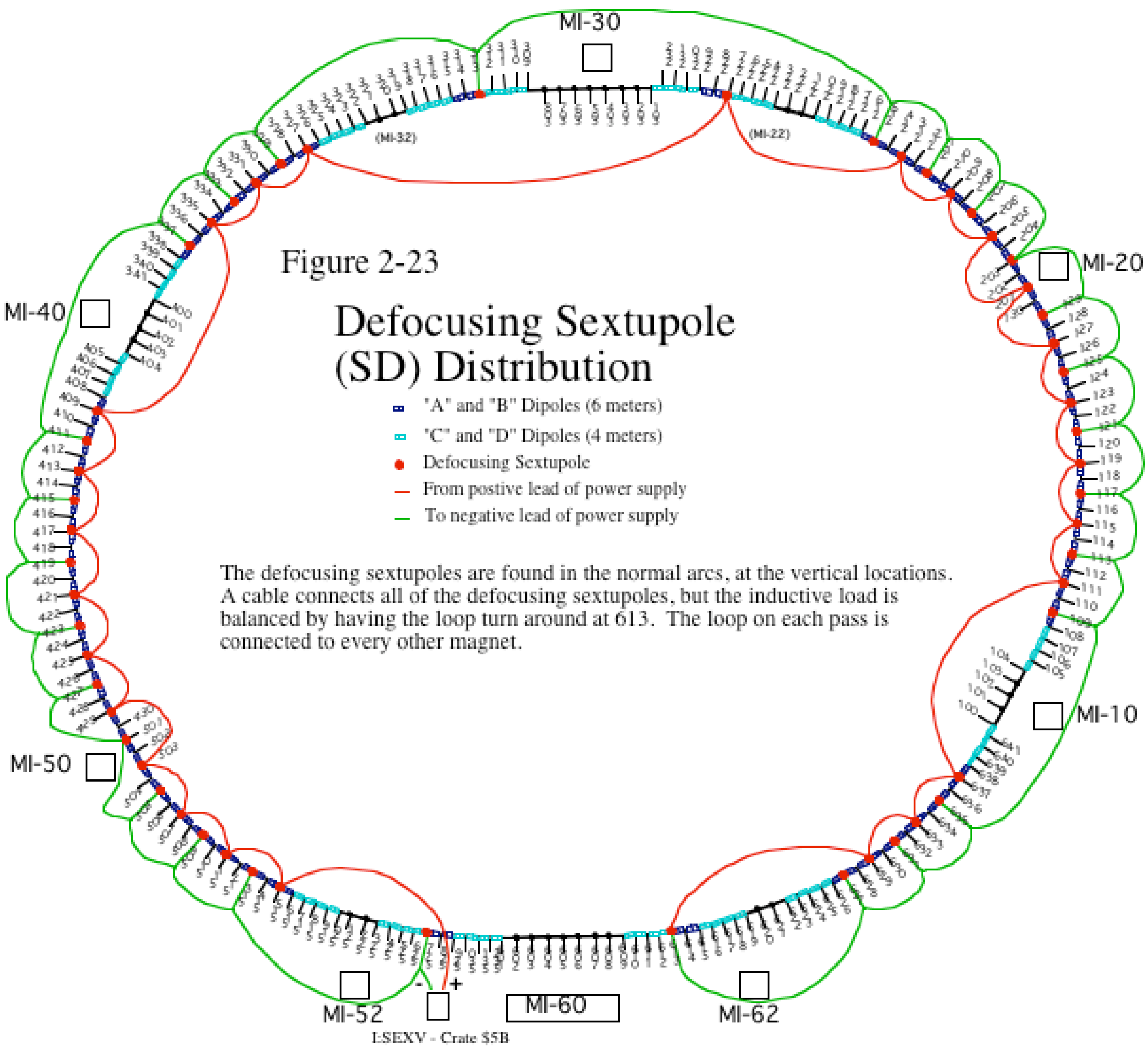
The 16 trim quads are also arranged into four groups (Fig. 2-21). Notice that all of them are found at horizontal locations. The process of resonant extraction requires large changes in the horizontal tune, not the vertical tune. There are no trim quads at the 214 location, but where they are found, they are given names beginning with “QC” (for “quad corrector”), followed by the location number.



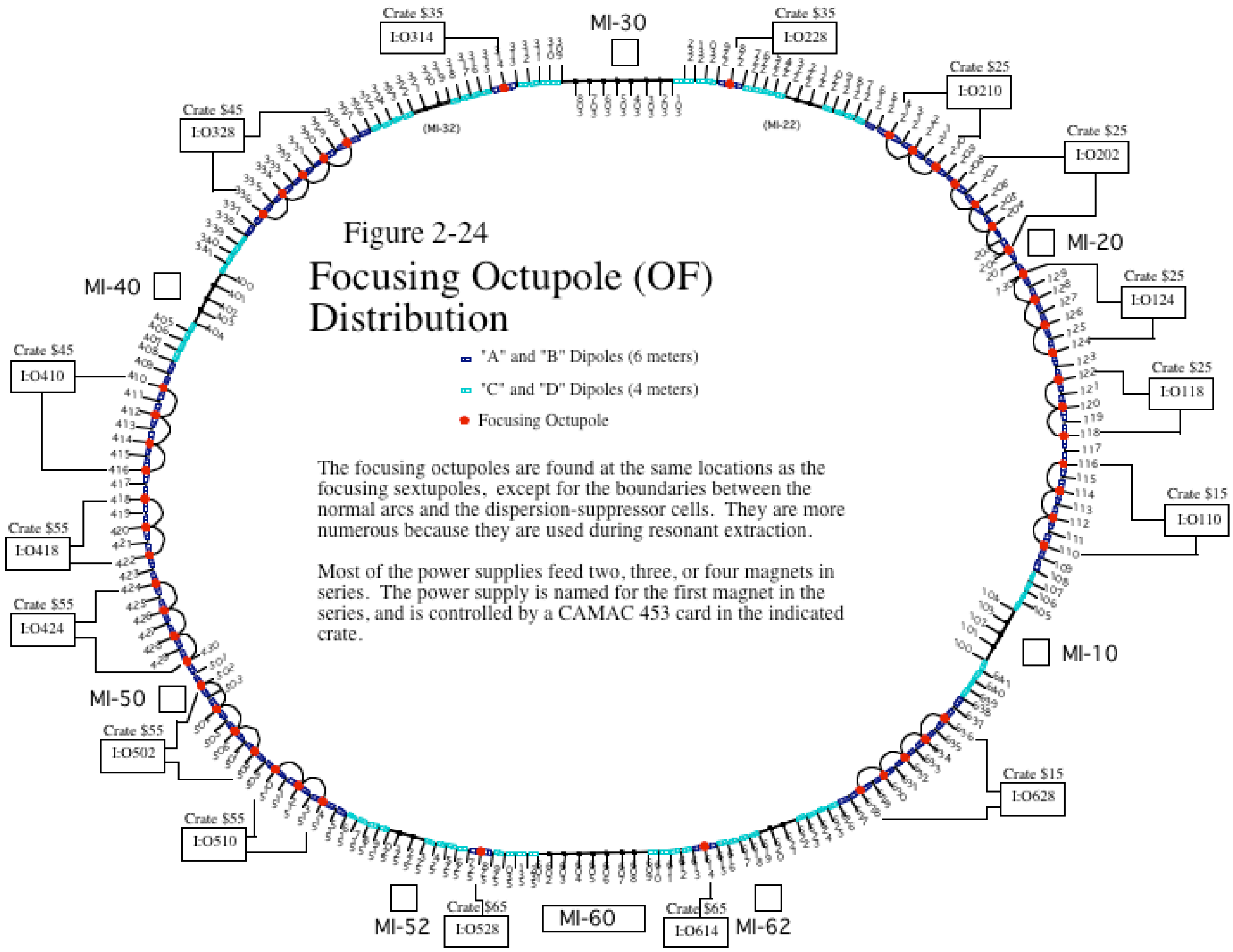
The sextupoles (Figs. 2-22, 2-23) are distributed at each location in the normal arcs: horizontal sextupoles at the focusing locations and vertical sextupoles at the defocusing locations. Remember that sextupoles use dispersion to compensate for variation in the momenta of the particles, so they would be of little use in the low- and zero-dispersion regions.



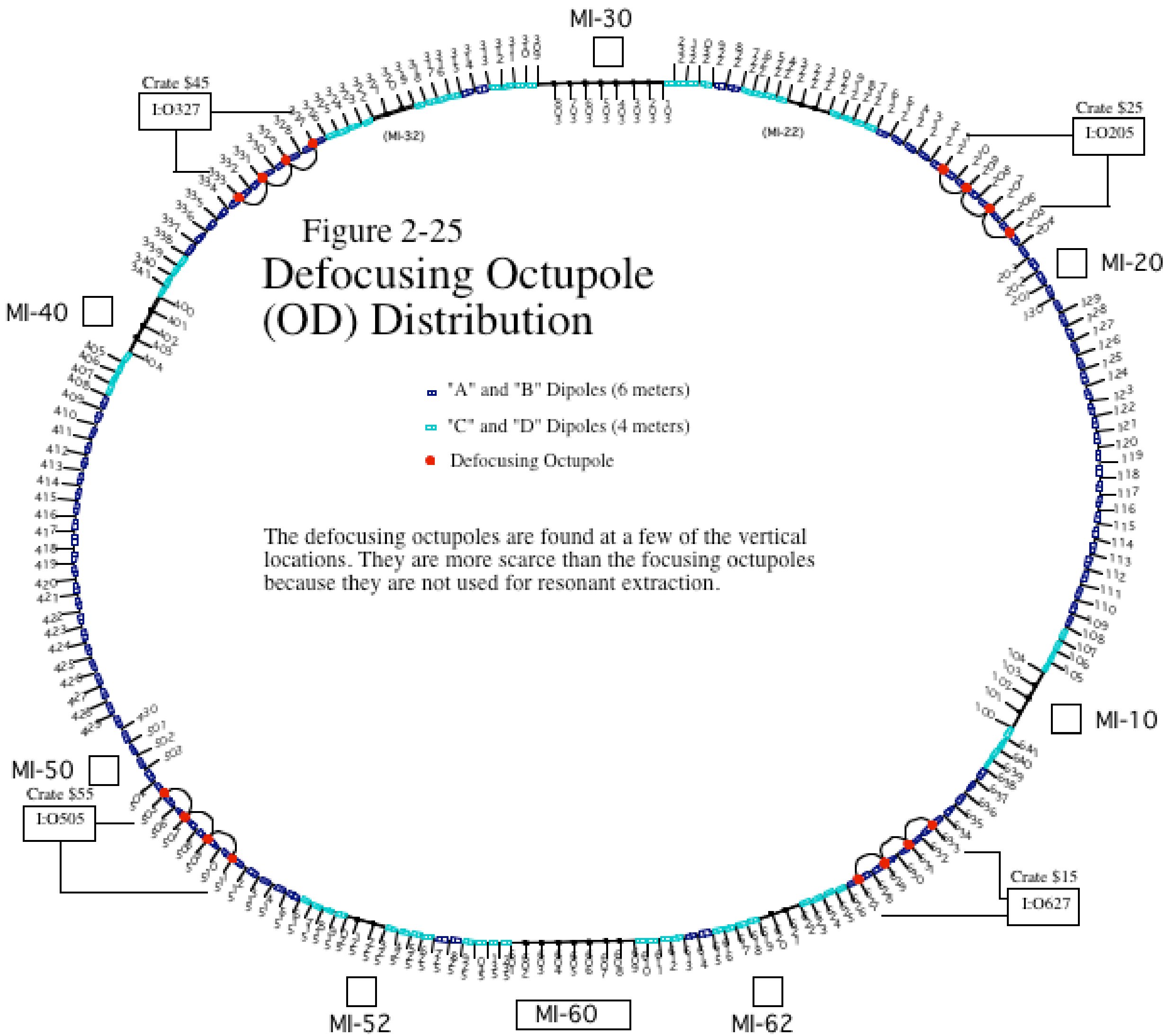
The sextupole at location 214 is named "S214."



The octupoles (Figs 2-24, 2-25) are used to stabilize circulating beam, but are also used for resonant extraction. There are only 16 octupoles at the vertical locations, but 50 at the horizontal locations. (The horizontal octupoles are present wherever the horizontal sextupoles are found, except at 108, 326, 408, and 626; the vertical octupoles are grouped into four clusters of four magnets.)



The preponderance of the horizontal octupoles is due to their importance during resonant extraction. The octupoles are named with an "O" in front of the location name; at this location, the octupole is called O214.



More detail on the trim quads and extraction octupoles will be discussed in the chapter on resonant extraction.

Remember, whether or not a magnet is focusing or defocusing does not need to be explicitly designated in its name, since the "evenness" or "oddness" of the location number encodes that information.

The next chapter, “Power Supplies,” is the story of how the magnets get their current.